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EFFECTS OF BACKPACK VOLUME ON THE BIOMECHANICS OF LOAD CARRIAGE

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13. ABSTRACT *(Maximum 200 words)*
METHOD: 12 men walked and ran while carrying (1) A MOLLE Standard pack, medium in height, width, anterior-posterior dimension, and distance from pack center of mass to the load carrier's back, with low impediment to rearward arm swing, (2) A MOLLE Extended pack, medium in height, wide, of large anterior-posterior dimension, with great distance from pack center of mass to load carrier's back, and with medium impediment to rearward arm swing, and (3) A SPEAR pack, tall in height, wide, of medium anterior-posterior dimension, with relatively low distance from pack center of mass to load carrier's back, with high impediment to rearward arm swing. RESULTS: During walking, the MOLLE Standard produced the longest stride length, greatest degree of hip extension, highest relative braking, ankle, and knee forces, and highest ground reaction moment. During running, it produced the most trunk movement, greatest rearward arm swing and arm swing range, smallest lateral distance between arms and trunk, lowest maximum upward center of mass velocity, lowest ankle-angle range, greatest degree of knee straightening, and greatest degree of hip extension. During walking, the MOLLE Extended produced the most forward trunk lean and lowest hip-flexion torque. During running, it produced the greatest minimum distance from arm to trunk, highest center of mass upward velocity, greatest ankle angle range, least knee straightening, most hip extension, and highest hip flexion torque. During walking, the SPEAR produced the shortest stride length, least rearward arm swing, most forward arm swing, greatest distance from arm to trunk, lowest peak body downward velocity, lowest relative ankle and knee force, least unweighting, and greatest knee and hip flexion torques. During running, it produced the least forward trunk lean, least trunk angle range, least rearward arm swing, greatest forward arm swing, highest minimum and maximum body positions, lowest hip flexion torque, and lowest medial forces and impulses. The only direct effects of pack volume appeared related to lateral protrusion that impeded arm swing. The other effects appeared indirect, due to such factors as pack center of mass and moment of inertia.

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BACKGROUND

USARIEM BIOMECHANICS RESEARCH PROGRAM

In 1984, a biomechanics research program was established at USARIEM. Because of its relevance to the Army, load carriage was selected as a major area of focus of the program.

NATICK SOLDIER CENTER / USARIEM JOINT LOAD CARRIAGE PROGRAM

In 1999, a joint program of the Natick Soldier Center and USARIEM entitled "Load Carriage Optimization for Enhanced Warfighter Performance" was established to carry out applied research on load carriage. The program, which will extend through fiscal year 2003, has been deemed a high-priority effort by both the Department of Army (DA Science and Technology Objective IV.G.14) and the Department of Defense (DoD Technology Objective M12).

DEVELOPMENT OF NEW MILITARY LOAD CARRIAGE SYSTEMS

The U.S. Army is currently undertaking two programs that involve development of load-carriage systems: the Modular Lightweight, Load-carrying Equipment (MOLLE), and the Special Operations Forces Personal Equipment Advanced Requirements (SPEAR) programs. The MOLLE, which is to replace the All-purpose Lightweight Individual Carrying Equipment (ALICE), is intended for use by most U.S. Army and U.S. Marine Corps personnel, and is the load-carrying equipment for the developmental Land Warrior system. The SPEAR is for Special Operations Forces, while the Land Warrior is a digital soldier system that will be fielded to high priority units, such as the 82nd Airborne Division. These systems combine an integrated load-carriage vest for the fighting load, small packs of various dimensions for the approach load, and a combination of the small packs and a large backpack for the sustainment load.

Pack Volume and Shape Considerations

The dimensions of the packs and associated components of MOLLE and SPEAR systems are based on the need to accommodate mission-essential items (Operational Mode Summary for the SPEAR Body Armor/Load Carrying System, 1997; Operational Requirements Document of the Modular Load System, 1995; Specification A3246133, April 1996). In both new systems, the minimum volume required is greater than the volume of the ALICE. For example, the large ALICE pack has a capacity of 64 liters and the desired capacity of the MOLLE, including a butt pack, patrol pack, main pack, and sleeping system, is 110 liters.

Although there is concern among U.S. Army and U.S. Marine Corps personnel that weight carried will increase as pack volume increases, little attention has been given to the effects the concomitant increase in the dimensions of load-carriage

systems will have on a soldier's mobility on the battlefield. This issue is particularly critical at the present time, with the renewed emphasis by the U.S. Army and the U.S. Marine Corps on the conduct of military operations in urbanized terrain (MOUT), where soldiers must operate in and around man-made structures and facilities (11). Furthermore, in the case of the Land Warrior system, which is to be used in MOUT environments, both the volumes and the shapes of the fighting, approach, and sustainment loads are being greatly impacted by the digitized instruments and their auxiliary components that comprise the system (Specification A3246133, 1996). Designers of the load-carriage equipment now under development are therefore presented with the challenge of producing large-volume backpacks that are compatible with operations being conducted in confined, man-made environments by troops who must be highly agile. There is little information in the load-carriage literature to guide the design of new systems that will meet these requirements.

MILITARY RELEVANCE

The present study is one of a series being done as part of the program to improve the design of load-carrying systems. In this study, the issue of the effects of backpack volume, shape, and external dimensions on soldier's physical performance is being addressed. Technologists at the Natick Soldier Center have an immediate need for information on this topic to apply to on-going equipment design projects for the Army and the Marine Corps. Programs currently underway to develop new military load-carrying systems include requirements for backpacks much larger in volume than the currently used ALICE equipment. However, developers of the equipment and military user representatives lack information concerning the effects of increased pack volume and dimensions on the soldier. The findings from this study will be used to guide the design of the new systems and the development of operational requirement documents for future load-carriage equipment programs.

ACKNOWLEDGMENTS

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LIST OF SYMBOLS, ABBREVIATIONS, AND ACRONYMS

USARIEM	U.S. Army Research Institute of Environmental Medicine
SBCCOM	U.S. Army Soldier, Biological, and Chemical Command
ALICE	All purpose, lightweight, individual carrying equipment
MOLLE	Modular Lightweight, Load-carrying Equipment
SPEAR	Special Operations Forces Personal Equipment Advanced Requirements
MOUT	military operations in urbanized terrain

EXECUTIVE SUMMARY

To assess the effects of backpack volume on gait biomechanics, motion analysis of load carriage was performed using a computerized video system and force platform. Twelve male military volunteers (22.0±3.5 yrs, 180.0±8.2 cm, 80.1±10.0 kg) walked at 1.32 m/s (3.0 mi/hr), a medium walking speed, and ran at 2.91 m/s (6.5 mi/hr), a medium jogging speed, while carrying (1) A MOLLE Standard pack, which was medium in height above the belt, in width, in anterior-posterior dimension, and in distance from the pack center of mass to the load carrier's back, with low impediment to rearward arm swing, (2) A MOLLE Extended pack, which was of medium height above the belt, wide, of large anterior-posterior dimension, with relatively great distance from the pack center of mass to the load carrier's back, and with medium impediment to rearward arm swing, and (3) A SPEAR pack, which was tall in height above the belt, wide, of medium anterior-posterior dimension, with relatively low distance from the pack center of mass to the load carrier's back, and with high impediment to rearward arm swing. The individual pack characteristics accounted for the following differences observed between the packs in walking and running kinematics and kinetics:

During walking, the MOLLE Standard produced the longest stride length, greatest degree of hip extension, highest braking, ankle, and knee forces divided by loaded subject weight, and highest ground reaction moment. During running, it produced the largest sagittal plane trunk angle range, greatest rearward arm swing and arm swing range, smallest lateral distance between the arms and trunk, lowest maximum upward center of mass velocity, lowest ankle-angle range, greatest degree of knee straightening, and greatest degree of hip extension.

During walking, the MOLLE Extended produced the greatest amount of forward trunk inclination and the lowest hip-flexion torque. During running, it produced the greatest minimum lateral distance from the arm to the trunk, the highest center of mass upward velocity, the greatest ankle angle range, the least straightening of the knee, the most hip extension, and the highest hip flexion torque.

During walking, the SPEAR produced the shortest stride length, least rearward arm swing, most forward arm swing, greatest lateral distance from the arm to the trunk, lowest peak downward velocity of the center of mass, lowest ankle and knee force divided by loaded subject weight, least unweighting during the stride, and the greatest knee and hip flexion torques. During running, it produced the least forward trunk lean, the least trunk angle range, the least rearward arm swing, the greatest forward arm swing, the highest minimum and maximum positions of the center of mass during the stride, the lowest hip flexion torque, and the lowest medial forces and impulses.

It appears that the only direct effects of pack volume were related to lateral protrusion that impeded arm swing. The other effects were indirect, and appear to have been due to such factors as pack center of mass location and moment of inertia.

There appears little reason to do further research on the biomechanical effects of pack volume on running or walking in an open area, since volume appears to directly affect gait only when free arm swing is impeded or when the pack itself impedes locomotion in narrow or oddly-shaped passageways. While the effects of the important variable, pack center of mass location, have already been established, research is needed on the effects of backpack moment of inertia.

INTRODUCTION

While there have been studies on the effects of backpack volume on agility and other aspects of physical performance (23, 30), there has been no published research on the effects of backpack volume on the biomechanics of gait.

KINEMATIC ASPECTS OF GAIT

Studies of human gait are inherently complex because of the interrelationships among the various parameters that describe walking and running. Several studies have shown that gait parameters are affected by various factors. For example, walking velocity affects such kinematic parameters as the frequency and amplitude of leg movement, the range of motion of lower extremity joints, percentage of time for the stance and swing phases, percentage of the gait cycle in single- and double-support, vertical position of the center of gravity, stride time, stride length, angular limb motion, muscular activity, and joint reaction forces (8, 12, 13, 14, 15, 16, 19, 20, 21, 22, 27, 32, 33, 40).

KINETIC ASPECTS OF GAIT

Ground Reaction Forces

To kinetically analyze performances in which two parts of the body come into contact with an external object (which may include the ground), it is necessary to directly measure the force exerted by at least one of those body parts on the external object. This applies to activities such as walking, manual labor, and load carriage. The necessary information cannot be inferred from kinematic analysis alone, using video, goniometry or other equipment to track body movement.

During running, no more than one foot makes contact with the ground at any given time. Thus, it is possible to calculate forces and torques on the body from kinematic data and knowledge of the runner's body mass. However, during walking, both feet contact the ground at the same time during the two double-support phases of each full stride. Therefore, force platform data are required to enable a kinetic analysis. As the foot exerts force on the ground during the stance phase of a stride, the ground exerts equal and opposite force on the foot. The study of ground reaction forces during walking can provide relevant information about the mechanics of gait under various conditions. It provides a direct measure of impact forces on the foot, and thus is relevant to the understanding and prevention of lower extremity injuries.

Force platforms, which use sensing elements whose electrical characteristics change in proportion to the magnitude of applied forces, are used to measure the forces and moments applied by the foot on the ground. If a complete force and torque record of a footstep is to be obtained, each of the force and moment components must be sampled at a sufficiently high rate. An example of the use of force platform

technology is the diagnosis of hip joint problems through evaluation of the vertical component of ground reaction force during walking, decomposition of the force into the sum of sine waves of various frequencies and amplitudes, and description of the force in other mathematical terms (24). Bresler and Frankel (4) studied different characteristics of vertical ground reaction force measured on a force platform. Yamashita and Katoh (45) used a specially designed force platform to analyze the pattern of center of pressure during level walking.

Schneider and Chao (36) analyzed the ground reaction forces of 26 normal volunteers during walking. The curve of vertical ground reaction force as a function of time typically had a dual-hump shape with the second peak higher (114% of body weight) than the first (106% of bodyweight). When graphed as a function of time, vertical ground reaction force formed a pattern that was nearly symmetrical about a vertical line at 50% of the stance phase of each foot. The anterior-posterior (front-back) ground reaction force was not symmetrically distributed, with a larger peak propulsive force (19.0% of bodyweight) and a smaller peak braking force (15% of bodyweight). The waveform of the medio-lateral (side-to-side) ground reaction force was more irregular than that of the anterior-posterior ground reaction forces. The medial ground reaction force was predominant except at both ends of the stance phase. Vertical ground reaction forces have been found to be affected by walking speed (3, 25) and stepping cadence (39).

Force platform data have been used to determine foot impact forces during load carriage. In a study comparing innovative and current load carriage systems (15, 16), statistically significant effects of load carriage system were found on heel-strike, push-off, and lateral ground-reaction forces. The relative effectiveness of different types of boots in protecting the wearer from foot impact forces during load carriage was examined in a study of 2 current-issue Army boots, 5 prototype military boots, and 5 commercial hiking boots (17) and in a follow-up study of 2 current-issue Army boots, 1 current-issue Marine Corps boot, and 3 second-generation prototype boots (18). When volunteers walked over a force platform while carrying 27 kg backpacks, significant differences were found among the boots as to braking, vertical, and push-off ground-reaction forces. Other research on volunteers carrying loads between 6 kg and 47 kg, and walking between 1.17 and 1.50 m/s showed that ground-reaction forces increased both with load carried (19) and with speed of walking (20).

Joint Moments and Forces

An understanding of the effects of forces on material bodies is essential to the study of locomotion. The strength of a rotational impetus is called "moment of force" and is equal to the magnitude of the force multiplied by the perpendicular distance from the line of action of the force to the point of rotation. Kinetic analyses of walking (2, 36) and running (28, 31, 43) revealed basic patterns of moments generated by the muscles around the ankle, knee, and hip. However, individual differences in pattern of moments about the knee and hip during gait have also been noted (35, 43).

Simon et al. (37) investigated the forces generated at heel-strike during human gait using both a force platform and a force transducer inserted into the heel of the shoe. The output traces were analyzed for the existence of high frequency impulsive loads during a normal walking cycle. The data showed that during normal human gait, the lower limb is subjected to a high impulsive load at heel-strike. The severity of this impulse varied with the individual, the walking velocity, the angle with which the limb approached the ground, and the compliance of the two materials coming in contact at heel-strike. Peak force varied from 0.5 to 1.25 times bodyweight, and its frequency components varied from 10 to 75 Hz.

Paul (34) showed that average joint forces at both the hip and the knee increase with increasing stride length, while Stauffer et al. (41) observed that an increase in cadence during free walking in normal volunteers did not significantly change the magnitude of the peak compressive forces across the ankle joint.

In several other studies (28, 31, 43), basic moment patterns during running were revealed. Winter (43) studied ankle, knee, and hip moments while 11 normal volunteers jogged at slow speed. He found that the moment of force for the total lower limb was primarily extensor during the stance phase. He also noted the relative timing of the peak extensor torques at the three major lower body joints. Hip torque peaked at 20% of stance, knee torque at 40% of stance, and ankle torque near 60% of stance. The variability of the moment patterns across all jogging trials was considerably less than that seen during walking. Two power bursts were seen at the ankle, including an absorption phase early in the stance followed by a dominant generation peak during late push-off. Average peak power generation was 800 W, with individual maximums exceeding 1500 W.

Joint forces and moments have been measured during load carriage. The type of boot worn has been found to significantly affect the forces and moments experienced by the load carrier. In a study of 2 current-issue Army boots, 1 current-issue Marine Corps boot, and 3 second-generation prototype boots (18), volunteers walked over a force platform and in front of video cameras while carrying 27 kg backpacks. Significant differences of up to 3.5% were found among the boots as to bone-on-bone forces at the ankle, knee, and hip. An analysis of the effects of backpack weight on the biomechanics of load carriage showed that moments and forces at the ankle, knee, and hip increased with load carried over a range of 6-47 kg (19). For example, peak vertical bone-on-bone force at the knee was 47% higher for the 47 kg load than the 6 kg load, and peak knee-extension moment was 98% higher for the 47 kg load than the 6 kg load. Walking speed also affects joint forces and moments. In a study in which volunteers walked at 1.17, 1.33, and 1.50 m/s while carrying various loads (19), walking speed had a greater effect on horizontal than vertical joint forces. For example, at the fastest walking speed the vertical and horizontal forces at the knee were respectively 9% and 23% greater than at the slowest walking speed. Peak knee extension torque was 47% higher at the fastest than the slowest walking speed.

RELATIONSHIP OF GAIT MECHANICS TO ENERGY

Mechanical analysis of walking has been studied for many years (7). Cavagna and Margaria (5) introduced energy calculations from force platform data, with the body regarded as a point mass. Winter et al. (44) developed a mechanical energy calculation method based on a segment-by-segment analysis assuming energy exchanges within segments and energy transfer between adjacent segments.

Direct measurement of oxygen consumption during load carriage has been used in order to infer energy cost. In a study of 2 current-issue Army boots, 5 prototype military boots, and 5 commercial hiking boots (17), the oxygen consumption of volunteers was measured as they carried 27 kg backpacks while walking on treadmill at 1.3 m/s. Significant differences in oxygen consumption during walking, up to 11%, were found among the boots, which also produced corresponding differences in gait kinematics and kinetics.

PURPOSE OF THE PRESENT STUDY

Only a limited amount of research has been directed toward the biomechanical study of load carriage, and of that, none has been focused on the effects of backpack shape and volume. This study was undertaken to increase understanding of the effects of backpack shape and volume on the biomechanics of walking and running. The use of both video and force platform motion analysis provided the opportunity to determine both body kinematics and kinetics during the carriage of loads in backpacks of different shapes and volumes. The military relevance of the study was enhanced by the fact that the volunteers were soldiers and the MOLLE and SPEAR backpacks used in the study represent the latest U.S. military load carriage equipment.

This study was undertaken to generate information needed to form the basis of recommendations concerning pack systems. Quantitative biomechanical analysis of the effects of backpack volume on load carriage can potentially contribute to the process of equipment evaluation and design, resulting in improved load carriage systems. Knowledge-based improvements in pack design could aid all those who engage in load carriage by increasing transport speed, lessening the likelihood of injury, improving efficiency, and decreasing perceived level of difficulty. The information resulting from this study can also help those who establish volume requirements of new pack systems by elucidating the pros and cons associated with various pack volumes and shapes.

METHODS

LOAD CARRYING EQUIPMENT USED IN THE STUDY

The backpack systems used for the biomechanical testing were the MOLLE, a load carriage system based on an external frame backpack, and the SPEAR, a system based on an internal-frame backpack adapted from a commercial version. These packs were chosen because they are part of current U.S. Army load carriage systems. The MOLLE is intended for use by most U.S. Army (and U.S. Marine Corps) personnel, and is the load-carrying equipment for the developmental Land Warrior system. The SPEAR is for Special Operations Forces.

Modular Lightweight Load-carrying Equipment (MOLLE)

The MOLLE is a modular load carrying system that was adopted by the U.S. Marine Corps in April 1999 as the standard load-carrying equipment for its personnel, and is now being tested by the U.S. Army in anticipation of being adopted as the standard system for Army personnel. It is comprised of a load-carrying vest for fighting load components and a number of packs that can be attached to a molded polymeric external frame. The packs include a large rucksack and a smaller butt pack, patrol pack, sleep system carrier, and side pockets for the rucksack. The system's modularity allows soldiers or marines to tailor the system to accommodate mission-specific equipment and supplies. Most of the MOLLE components can be used independently of one another or together as a fully integrated system. The pockets on the load-carriage vest are removable and can be placed where they provide ready accessibility to the most needed items for the particular mission.

Special Operations Forces Personal Equipment Advanced Requirements (SPEAR)

In contrast to the MOLLE system, the SPEAR load-carrying system is based on an internal frame. Made by Gregory Mountain Products (Temecula, CA), it is a modified version of their commercial pack system. It is not modular and has a volume of 154.1 liters. It consists of a large main pack bag with large permanent pockets on each side that run the length of the pack, and a permanently attached sleep system compartment. There is also a large removable patrol pack. The adjustable shoulder straps and waist belt are heavily padded and contoured. As with the MOLLE system, the SPEAR system has a load-carrying vest of modular design to accommodate fighting equipment and supplies.

LOAD-CARRIAGE SYSTEM VOLUME CONDITIONS

Biomechanical testing was conducted on volunteers carrying loads under three different conditions in which the weights were virtually identical, but the volume configurations of the load-carriage systems were different. This allowed examination of

the effects of shape and volume independent of the weight carried. Figures 1-3 respectively show front and side views of the MOLLE Standard, MOLLE Extended, and SPEAR in their tested configurations. It can be seen that the MOLLE Standard was the smallest of the packs in volume, with little impediment to rearward arm swing; the MOLLE Extended protruded rearward more than the other pack systems; while the SPEAR was the highest of the three packs, extending above the wearer's head. Table 1 provides some quantitative information about the three different backpack configurations, and shows that while the loaded packs differed by only a small degree in mass, they differed considerably in volume; the MOLLE Extended had 2.7 times the volumetric capacity of the MOLLE Standard, while the SPEAR had 3.8 times the MOLLE Standard's volumetric capacity.

Figure 1. MOLLE Standard backpack as tested

Figure 2. MOLLE Extended backpack as tested

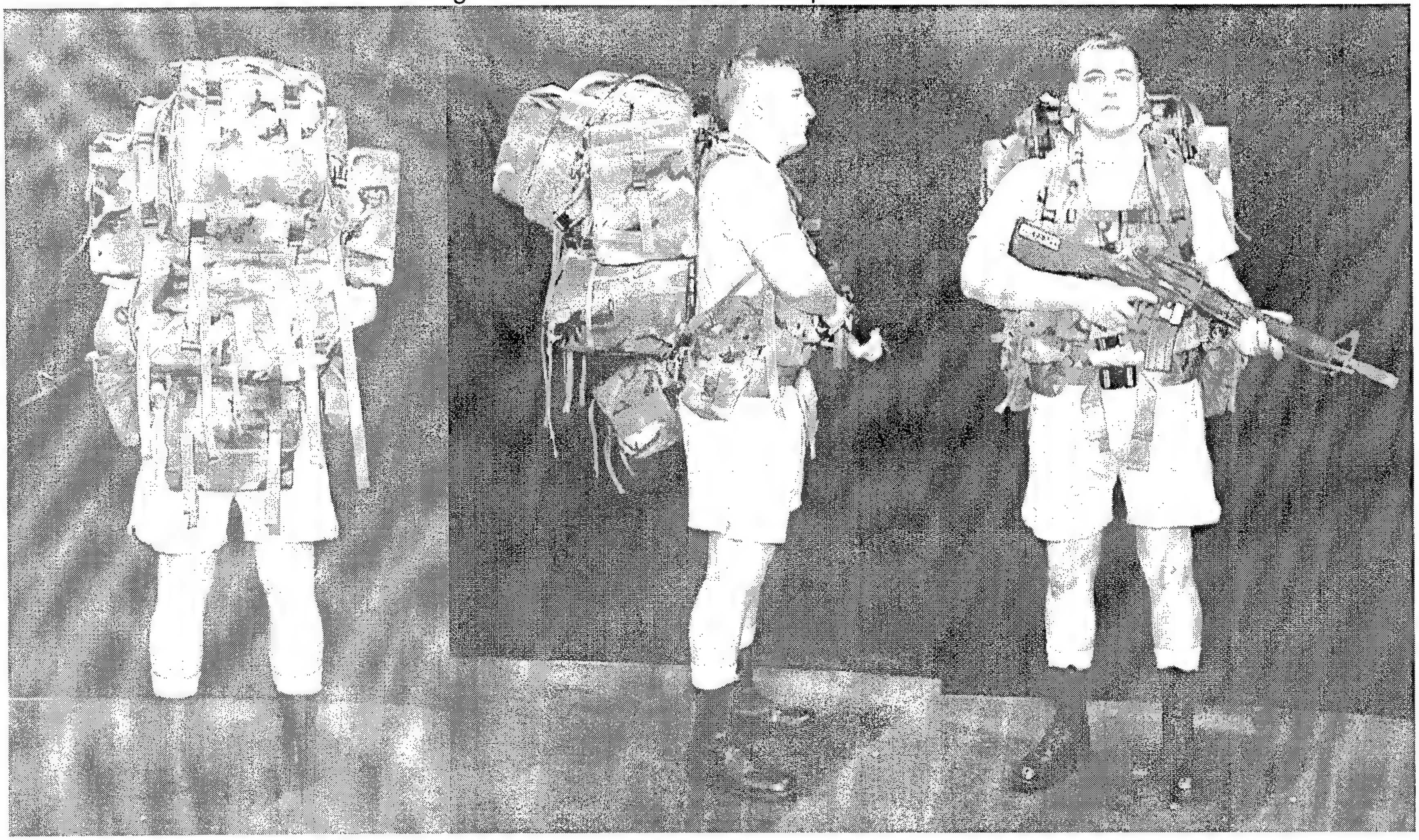


Figure 3. SPEAR backpack as tested

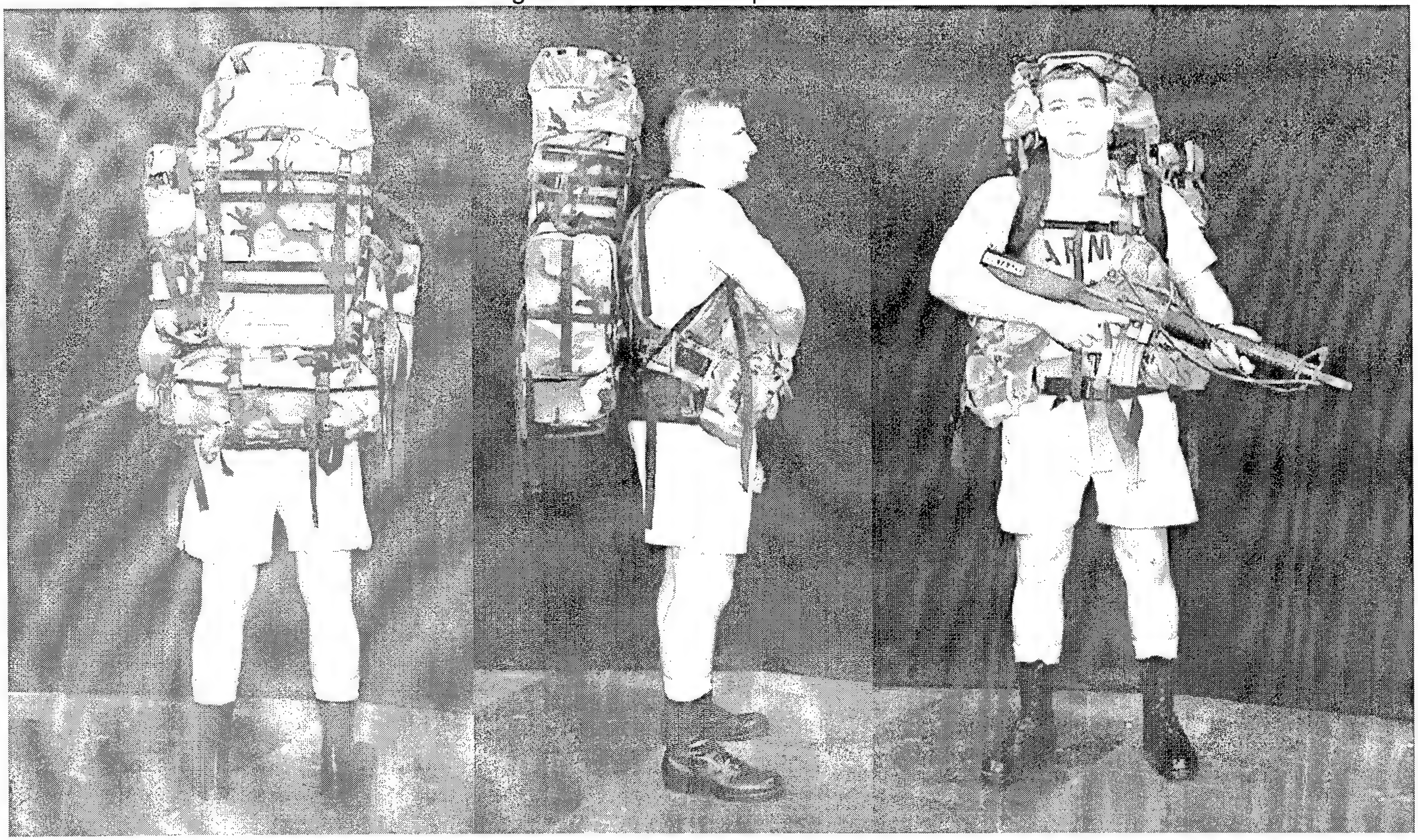


Table 1. The backpack systems used in the experiment

Pack System	Components	Empty Component Mass (kg)*	Loaded Component Mass (kg)ϕ	Pack Volume (l)
MOLLE Standard	MOLLE fighting vest, pack-frame, butt pack, rucksack, and rifle	5.5	20.4	40.6
MOLLE Extended	MOLLE fighting vest, pack-frame, butt pack, rucksack, rucksack sustainment pockets, patrol pack, sleep system bag, and rifle	7.6	20.6	108.6
SPEAR	SPEAR fighting vest, large internal frame pack, patrol pack and rifle	7.8	21.1	154.1

The rifle was an inoperable M16A1 carried in both hands in front of the body.
Mass of the empty fighting vest was 1.8 kg for the MOLLE and 1.7 kg for the SPEAR
* Includes all components listed, with the exception of the rifle, devoid of any contents
ϕ Includes all components listed, as loaded for the study, including the rifle

In their study of load weight and volume effects, Holewijn and Lotens (23) included some test conditions in which only lightweight foam blocks were carried by the participants. When the total weights of loads placed in backpacks are low, the load-carrying equipment can be very unstable, with the equipment center of mass showing large displacements in the horizontal and the vertical directions relative to the body center of mass. Holewijn and Lotens avoided this problem by employing a special test device that secured the load to the body, instead of using load-carrying equipment. In the present study, weights were placed in the packs such that the total masses of all components comprising each of the 3 different load conditions, including the backpack frame, all pack bags and their contents, straps, belts, loaded fighting vest, and rifle were similar at 20-21 kg. Using pack weights in this range, rather than very light loads, minimized their horizontal and vertical displacements relative to the body. Even with the additional weight of the boots and gym clothing worn by each volunteer, which amounted to about 2 kg, the total mass worn and carried by the study participants was well under the 32.7 kg deemed as the maximum load that should be carried on "prolonged, dynamic operations" (10).

Identical items were carried on the MOLLE and the SPEAR vests, and identical removable pockets were placed in the same locations on them. A single vest configuration was employed throughout the study -- that of a rifleman's fighting load. Two double pockets, each containing 60 dummy rounds of M-16 ammunition, were attached to the front of the vest, along with two single pockets, each holding a dummy 30-round M-16 magazine. There were two additional single pockets, each containing one dummy fragmentation grenade. A utility pouch loaded with 60 dummy rounds of M-16 ammunition and a 1-quart canteen filled with water were placed on the waist belt. The mass of each load-carrying vest, including the vest, belt, pockets, and items, was 8.7 kg.

The SPEAR pack was filled completely with foam. Because it was heavier than the MOLLE packs, weights in the form of steel plates were placed in the MOLLEs to equalize the pack masses. The plates were positioned at the pack center of volume and held in place with foam blocks. Foam material was also added as needed to expand the packs and any attached pockets to their maximum external dimensions. There remained small differences in pack system weights despite the attempt at equilibration.

In order to provide a basis for understanding any differences in the biomechanical variables among the three pack systems tested, various measurements of the systems were made and are shown in Table 2. Centers of mass were calculated using a reaction board according to the technique of Winter (42).

Table 2. Various measurements of the test pack systems (cm)

	Pack System		
Measurement	MOLLE Standard	MOLLE Extended	SPEAR
width	41.0	65.5	59.0
mid-belt to top	57.5	60.0	87.0
mid-belt to bottom	27.0	27.0	7.0
total height	84.5	87.0	94.0
anterior-posterior	32.0	54.5	28.5
COM distance above belt	21.6	25.3	20.6
COM distance behind back	6.1	11.2	-3.8

COM = center of mass

VOLUNTEERS

Sample Size Estimation

The procedure of Cohen (6) was used to estimate the required sample size for the study. For a two-tailed analysis of variance at a significance level of .05, a sample size of 12 was deemed sufficient to detect an effect size of 0.30 standard deviation units at a power level of 0.70.

Participants in the Study

The 12 research volunteers were recruited from among the enlisted personnel (men and women) who served as human research volunteers assigned to Headquarters and Headquarters Detachment, U.S. Army Soldier Systems Center, Natick, MA. Potential volunteers were asked to participate after being informed of the purpose of the study, the nature of the test conditions, the risks associated with the study, all procedures affecting a volunteer's well-being, and a volunteer's right to discontinue participation at any time without penalty. Those who agreed to participate in the study signed a Volunteer Agreement Affidavit (DA Form 5303-R). Each volunteer was given a copy of the signed affidavit. The investigators adhered to the policies for protection of human subjects as prescribed in Army Regulation 70-25.

Participation in the study was limited to men and women under the age of 36 who could be properly fitted in the available waist belts worn with the MOLLE and SPEAR backpacks and who were found by the Human Research Medical Officer or his designee to be in good physical health. Before participating in the study, the Human Research Medical Officer or his designee screened all volunteers through physical examination, routine blood testing, and clinical review of medical records, with an emphasis on the musculoskeletal system. Care was taken to exclude individuals with histories of back problems, including herniated intervertebral discs, or previous orthopedic injuries that limited range of motion about the shoulder and knee joint. Pregnant women were excluded from the study.

INSTRUMENTATION

Force Platform System

Information needed for the kinetic analysis of load carriage includes the forces exerted by the ground on the feet (ground reaction forces). A force platform provides the needed information because the ground reaction forces are equal in magnitude to, and opposite in direction from, the forces exerted by the feet on the force platform. Information provided by the force platform includes the magnitudes of forces exerted by the feet in the vertical, anterior-posterior, and medio-lateral directions relative to the walker, as well as the location on the platform of the foot center of pressure. Knowledge of the latter is essential in order to obtain the moment about the ankle joint, which is calculated as the product of the ground reaction force and the distance from the point of application of the force to the ankle joint. Accurate determination of center of pressure is important because errors in this measure cause error in calculation of the torque about the ankle joint, leading to a cascade of errors in torque calculations up the kinetic chain, including those for the knee and hip.

A model LG6-1-1 force platform from Advanced Mechanical Technology Incorporated (Newton, MA) was used in conjunction with a model SGA6-3 amplifier designed for use with computerized data acquisition systems. To make it flush with the floor, the platform, which measured 0.61 by 1.22 m (2 by 4 ft), was mounted on a steel frame in a custom-made cavity in the concrete laboratory floor. The frame kept the force platform rigid and isolated it from external vibrations that might have caused spurious output signals. The no-damage limits of the platform were 9,800 N (2,200 lb) of vertical load applied anywhere on the top surface, or 6,700 N (1,200 lb) of horizontal load applied perpendicular to any of the platform's sides. The system was designed to emit voltage signals proportional to forces exerted on the plate's surface in the vertical, anterior-posterior, and medio-lateral directions and torques around a set of orthogonal axes through the center of the plate. Center of pressure could be calculated from the forces and torques, as specified in the AMTI force platform manual (1). The SGA6-3 amplifier system contained a six-channel amplifier with switch-selectable gains of 1000, 2000, and 4000 for each channel. Each channel also had a selectable low-pass filter with a 10 Hz or 1,050 Hz cut-off frequency and selectable precision bridge excitation voltages of 2.5, 5, or 10 V.

Motion Analysis System

A video motion analysis system (Qualisys, Glastonbury, CT) using six cameras recorded the body movements of the volunteers in three dimensions as they walked across the force platform. The sampling frequency of the cameras was 120 Hz. The computer recorded the ground reaction forces from the force plate as the volunteer stepped on it.

Under the assumption of bilateral symmetry, segmental movement data for the left side of the body were generated by phase shifting the right side data by 180°. A 12-

segment model of the human body was constructed (two feet, two shanks, two thighs, two forearms, two upper-arms, a trunk and a head), and the mass inertial properties of the segments were taken from estimates given by Dempster (9). A custom-written software program performed a standard link segment analysis frame-by-frame for a single stride. The single stride selected for analysis was centered on the point where the right foot struck the force plate. The stride was defined as that portion of the gait cycle starting from when the right foot crossed in front of the left leg to when the right foot next crossed in front of the left leg. The custom program calculated the location of the body center of mass as described by Winter (42) and plotted its coordinates for each frame of video data. The program also determined stride length, stride frequency, and body segment displacements, velocities, and accelerations. Joint reaction forces at the ankle, knee, and hip joints were calculated using inverse dynamics.

The vertical and horizontal distances between the load center of mass and the body center of mass were calculated for each frame during the stride. The load center of mass was determined by affixing the loaded pack and load-carrying vest to a foam torso dummy, and placing the assembly on a balance board, while the body center of mass was obtained by standard biomechanical analysis (42). The mean vertical and horizontal distances over the entire stride were then calculated from the frame-by-frame data for a trial. These mean values are given as the vertical and horizontal distances for that trial.

For each frame of video data, the coordinates of a reference point on the trunk were calculated as the midpoint of a line segment connecting the right and left shoulders. The vertical and horizontal distances between the pack center of mass and the trunk reference point were then calculated for each frame during the stride. The relative motion between the pack and the body both vertically and horizontally was assessed by calculating the standard deviations of the vertical and horizontal distances over the stride. The standard deviations of the mean vertical and horizontal distances calculated from the frame-by-frame data are given as the relative pack motion for a given trial.

In the sagittal plane, the minimum and maximum trunk, shoulder, hip, knee, and ankle angles (Figure 4) were determined as a means of analyzing posture throughout the stride. The trunk angle was defined as the angle of the trunk segment relative to vertical. For a subject facing towards the right, the trunk angle was positive when extending clockwise from the vertical and negative when extending counter-clockwise from the vertical. The shoulder angle was the ventral angle between the trunk and the upper arm, having a positive value with the upper arm in front of the trunk and a negative value with the upper arm behind the trunk. The hip angle was defined as the ventral angle between the thigh and trunk segments. The knee angle was defined as the dorsal angle between the thigh and shank segments, and the ankle angle was defined as the ventral angle between the shank and foot segments. In the frontal plane, the minimum and maximum hip and shoulder angles were determined, and are referred to as abduction-adduction angles. For these angles, a positive value is lateral to the midline of the body, while a negative value is ventral to the midline.

Figure 4. The system of body angles used to analyze posture throughout the stride

STA Sagittal Trunk Angle: the sagittal angle between the trunk and a vertical line (positive = forward lean; negative = backwards lean).

SSA Sagittal Shoulder Angle: the sagittal angle between upper arm and trunk (positive = upper arm in front of trunk; negative = upper arm behind trunk).

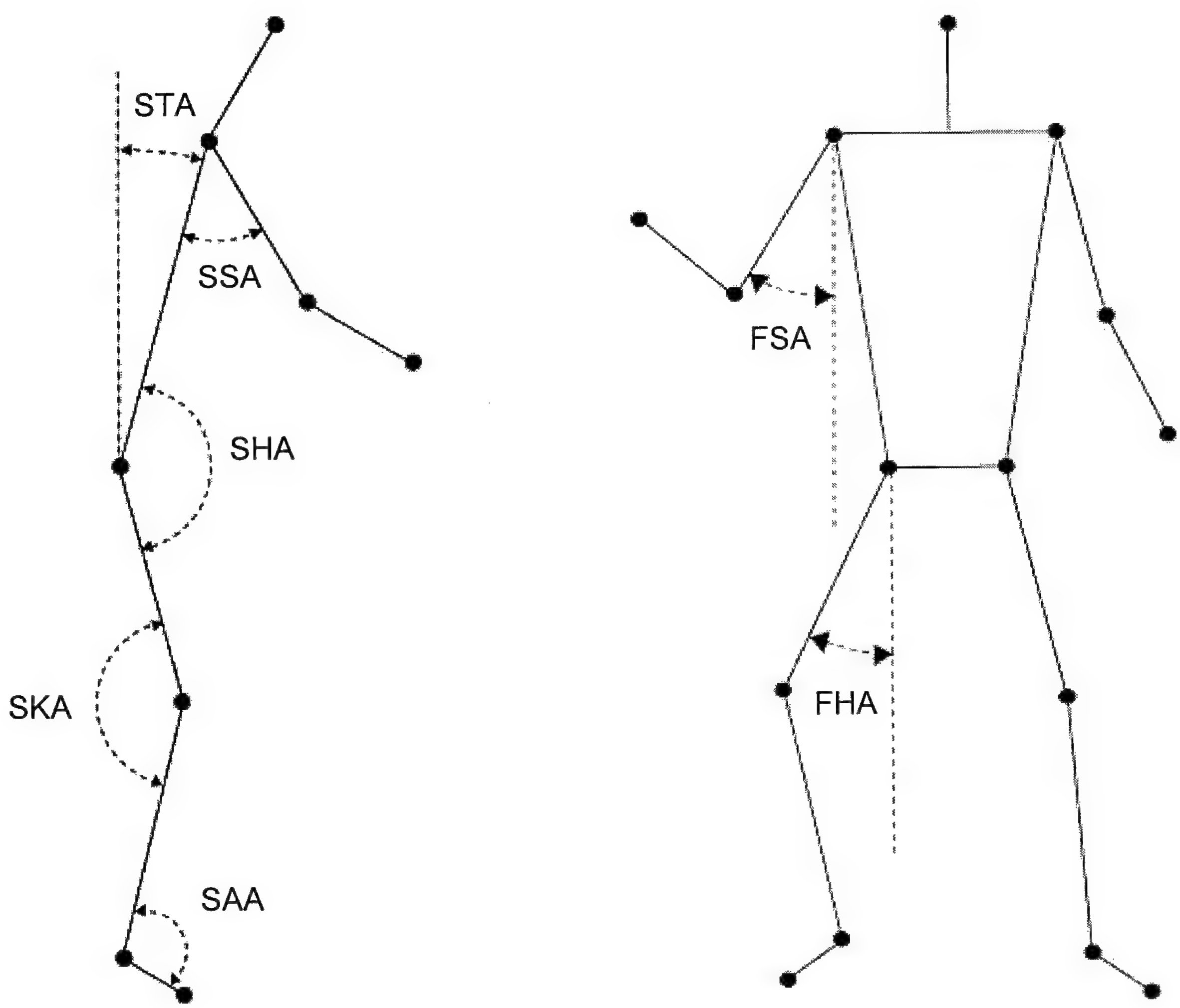
SHA Sagittal Hip Angle: the sagittal ventral angle between thigh and trunk.

SKA Sagittal Knee Angle: the sagittal dorsal angle between shank and thigh.

SAA Sagittal Ankle Angle: the sagittal ventral angle between foot and shank. Because the foot segment endpoints were the lateral malleolus and ball of the foot, with the bottom of the foot at 90° to the shank, the ankle angle was about 120°.

FSA Frontal Shoulder Angle: the frontal angle between the upper arm and the body midline (positive is lateral and negative is medial).

FHA Frontal Hip Angle: the frontal plane angle between the upper leg and the body midline (positive is lateral and negative is medial).



Due to the fact that the duration of a single stride varied across subjects, it was necessary to normalize the differing time scales to allow for the direct comparison of the timing of events within the gait cycle across subjects. This was accomplished by expressing the time course of all the biomechanical variables as a percentage of the stride cycle.

Speed Cuing Device and Speed Trap

A device to pace the volunteer's walking or running speed was designed at the U.S. Army Research Institute of Environmental Medicine and fabricated at the U.S. Army Soldier Systems Center in Natick, MA. It was based on a motor-driven cord marked with alternating light and dark bands that traveled around two pulley-wheels spaced 8 m apart. Turning a knob on the cuing device set the speed of the cord, which was displayed digitally to the nearest 0.01 m/s. During an experimental trial, the device was positioned alongside the volunteer so that the visible part of the cord traveled in the direction the volunteer walked. The volunteer walked or ran straight ahead while maintaining a peripheral view of the moving cord, which cued the appropriate walking speed.

A speed trap, consisting of two sets of infra-red beam sensors and a timing system with telemetry (Brower Timing Systems, Salt Lake City, UT), was centered about the force platform so that the actual speed of the volunteer walking or running across the platform could be determined immediately after the trial. If the volunteer's speed did not fall within 5% of the prescribed speed, the trial was repeated.

TESTING

Procedures

For this experiment, the sampling frequency of the cameras was 120 Hz and that of the force platform was 1,000 Hz. Kinematic and kinetic data were acquired as the volunteers walked on a level floor at 1.32 ms^{-1} (3.0 mph) and ran at 2.91 ms^{-1} (6.5 mph) in each of the experimental load configurations. The kinematic data for one full stride, consisting of a left and a right step, were analyzed to determine the extent to which temporal gait parameters, body posture, and distances between load and body centers of mass differed over the load volume conditions. A number of variables were derived from the kinematic data including stride length and frequency; double support time; trunk, hip, knee, and ankle joint angles; and horizontal and vertical distances between load and body centers of mass. The kinetic data were used directly to assess the effects of the different backpacks on ground reaction forces, and in combination with the kinematic data to determine bone-on-bone forces at the major body joints, and the torques exerted by muscles around those joints throughout the stride. Peak values were determined for each variable, as well as the times of occurrence of those peaks as percentages of time for the entire stride.

Prior to testing, spherical reflective markers, approximately 2.5 cm in diameter, were affixed to the volunteer's skin on the right side of the body, and the right boot, using double-sided tape. Markers were placed on the right side of the body at the base of the 5th metatarsal, the lateral malleolus of the ankle, the lateral femoral condyle of the knee, the greater trochanter of the hip, the acromion process of the shoulder, the zygomatic arch of the head, the lateral epicondyle of the elbow, and the radial styloid process of the wrist. An additional marker was placed at the location of the sagittal plane center of mass of the backpack, which was determined by placing the loaded pack and the load-carrying vest on a lightweight, foam torso dummy and using the balance board center of mass location method methodology described by Winter (42).

During the walking and the running trials, a volunteer walked or ran about 13 m across the force platform and within the field of view of the motion analysis system. The volunteer's speed was paced by the custom-built speed-cuing device described above. The electronic timing device ensured that the volunteer maintained the set pace ± 5%. Each volunteer was given practice trials to adjust walking or running speed and starting position so that the right foot landed squarely on the force platform as the volunteer passed across it. Occasionally, a trial had to be repeated if the volunteer's foot did not land directly on the force platform. Such trials, and those in which the volunteer's walking or running speeds did not fall within the acceptable ranges, were repeated. Data from the force platform and motion analysis system were collected for every trial, but only the data from acceptable trials were saved. The force platform captured ground reaction forces as the volunteer walked or ran across the plate, while the 6-camera video motion analysis system tracked the locations of the reflective markers on the subject and pack. The cameras were positioned to capture at least one complete stride over the force platform. Adequate rest periods were allowed between trials to avoid fatigue as a confounding factor. Each trial lasted no more than 15 seconds, so total exercise time per day was minimal.

Each volunteer participated in two biomechanical testing sessions. On one day, each volunteer performed all the walking trials for all the backpacks, and on another day, each volunteer performed all the running trials for all the backpacks. Each volunteer performed two acceptable trials per test condition. The order of presentation of the test conditions was balanced, so that the volunteers were no more likely to encounter a particular condition first, last, or in any intermediate position. All testing was conducted in the Center for Military Biomechanics Research, Building 45, Soldier Systems Center, Natick, MA.

Dependent Variables

The following variables were calculated from the vertical, anterior-posterior and medio-lateral forces exerted by the feet on the force platform:

a. heel-strike and push-off peak forces (N)
b. times of occurrence of heel-strike and push-off peak forces (% of stride time)
c. peak and average anterior-posterior and mediolateral forces (N)
d. positive and negative vertical, anterior-posterior, and mediolateral impulse per stride ($N \cdot s$)

Film analysis allowed calculation of the following:

a. joint ranges of motion for the shoulder, hip, knee, and ankle (degrees)
b. joint torques for the hip, knee, and ankle ($N \cdot m$)
c. joint forces at the hip, knee, and ankle (N)
d. stride length (m)
e. stride frequency (strides/min)
f. single-support time (% of stride time)
g. double-support time (% of stride time)
h. body segment and center of mass position, velocity, and acceleration

Data Processing

Data were collected and analyzed by computer. Computer programs performed the processing necessary to determine dependent variable values over the full stride. A statistical file was created that contained key variables describing the gait patterns of all the volunteers.

Statistical Analysis

The computer file containing the key variables describing the gait patterns of all the volunteers was used for statistical comparisons between the different experimental conditions. A one-way analysis of variance with repeated measures (SAS Institute Inc., Cary, NC) was performed on each of the variables, and a Duncan post-hoc test was used to identify significant ($p<0.05$) differences.

RESULTS

TEST VOLUNTEER CHARACTERISTICS

The test volunteers were all physically fit males, a bit above average in both height and body mass (Table 3), all of whom engaged in regular physical activity. The 12 volunteers were all from the test subject pool of the U.S. Army Soldier Center, Natick, MA.

Table 3. Physical characteristics of the test volunteers (means$\pm$SD)

Age (yr)	22.0$\pm$3.5
Height (cm)	180.0$\pm$8.2
Body mass (kg)	80.1$\pm$10.0
Gender	all male
n	12

EFFECTS OF PACK SHAPE AND VOLUME ON WALKING BIOMECHANICS

The dependent variables discussed in this section are those for which at least one statistically significant ($p<0.05$) difference was found between at least two of the three tested pack configurations.

Table 4 shows that stride length with the MOLLE Standard was significantly longer than with the SPEAR. The value for the MOLLE Extended fell between those for the other two packs, but did not differ significantly from either one. The shorter stride length for the SPEAR than the MOLLE Extended held when stride length was expressed as a percentage of each volunteer's height (Table 5). Even though the magnitude of the difference was small, just under 1%, it could be of practical significance. Stride length has sometimes been found to be shorter when the backpack is heavier (29). However, although the difference in stride length in the present study was in the direction expected due to the 3.4% greater weight of the SPEAR than the MOLLE Standard, the small magnitude of the weight difference was unlikely to have caused the difference in stride length. Previous research (16, 19) has shown that it takes much larger differences in weight to bring about comparable differences in stride length. Thus, it appears that some property of the SPEAR other than weight, such as load volume or shape, may be related to its shortening effect on stride length.

Table 4. Stride length (m) while walking at 1.32 m/s, mean (SD)

Load Carriage System		
MOLLE Standard	MOLLE Extended	SPEAR
1.553 [a] (0.068)	1.551 [a,b] (0.069)	1.539 [b] (0.077)

NOTE: Values superscripted with different letters are significantly ($p<0.05$) different

Table 5. Stride length divided by the volunteer's height while walking at 1.32 m/s, mean (SD)

Load Carriage System		
MOLLE Standard	MOLLE Extended	SPEAR
0.863 [a] (0.036)	0.862 [a,b] (0.028)	0.855 [b] (0.032)

NOTE: Values superscripted with different letters are significantly ($p<0.05$) different

Maximum heel-strike braking force (Table 6) was significantly higher for the MOLLE Standard than the SPEAR. Despite the fact that the SPEAR weighed 3.4% more than the MOLLE Standard, the MOLLE Standard produced 4.6% greater mean braking force. The possibility that this may have been due in part to the greater stride length with the MOLLE Standard is contradicted by the fact that the braking force with the MOLLE Extended was closer to that of the SPEAR than that of the MOLLE Standard, even though stride lengths with the two MOLLE versions were much closer to each other than to the SPEAR. This suggests a real volume effect, as the MOLLE Extended and SPEAR were both much larger than the MOLLE Standard. The MOLLE Extended was 2.7 times the volume of the MOLLE Standard, and the SPEAR was 3.8 times the volume of the MOLLE Standard.

Table 6. Maximum heel-strike braking force (N) while walking at 1.32 m/s, mean (SD)

Load Carriage System		
MOLLE Standard	MOLLE Extended	SPEAR
-203.3 [b] (26.61)	-196.8 [a,b] (22.49)	-194.4 [a] (22.46)

NOTE: Values superscripted with different letters are significantly ($p<0.05$) different

When maximum heel-strike braking force was adjusted for loaded subject weight (Table 7), the MOLLE Standard produced significantly higher braking force than both the MOLLE Extended and the SPEAR. The braking force with the MOLLE Standard was 5.6% higher than with the SPEAR and 4.0% higher than with the MOLLE Extended. The fact that the variable was adjusted to account for differences in loaded subject weight suggests a difference due to pack volume or shape

Table 7. Maximum heel-strike braking force divided by loaded subject weight while walking at 1.32 m/s, mean (SD)

Load Carriage System		
MOLLE Standard	MOLLE Extended	SPEAR
-0.209 [b] (0.038)	-0.201 [a] (0.032)	-0.198 [a] (0.032)

NOTE: Values superscripted with different letters are significantly ($p<0.05$) different

In keeping with the findings for heel-strike braking force, maximum resultant ankle joint reaction force divided by loaded subject weight (Table 8) was significantly greater for the MOLLE Standard than for the SPEAR. Even though the difference amounted to less than 2%, it is worthy of note because it could not be explained by the difference in pack weight, as this variable already incorporated an adjustment for weight. A lower joint reaction force is considered preferable for injury avoidance. The greater stride length with the MOLLE Standard than with the SPEAR may have accounted in part for the higher joint force. The value for the MOLLE Extended fell between those for the other two packs, but did not differ significantly from either one.

Table 8. Maximum resultant ankle joint reaction force divided by loaded subject weight while walking at 1.32 m/s, mean (SD)

Load Carriage System		
MOLLE Standard	MOLLE Extended	SPEAR
1.16 [a] (0.06)	1.15 [a,b] (0.04)	1.14 [b] (0.05)

NOTE: Values superscripted with different letters are significantly ($p<0.05$) different

A similar pattern was seen with maximum resultant knee joint reaction force divided by loaded subject weight (Table 9). Even though the variable incorporated an adjustment for weight carried, the MOLLE Standard produced a mean 1.5% greater force than the SPEAR. It appears that the MOLLE Standard was associated with gait changes that increased joint reaction force, an effect that could not be ascribed to differences in pack weight. The value for the MOLLE Extended fell between those for the other two packs, but did not differ significantly from either one.

Table 9. Maximum resultant knee joint reaction force divided by loaded subject weight while walking at 1.32 m/s, mean (SD)

Load Carriage System		
MOLLE Standard	MOLLE Extended	SPEAR
1.119 [a] (0.07)	1.110 [a,b] (0.05)	1.102 [b] (0.06)

NOTE: Values superscripted with different letters are significantly ($p<0.05$) different

The time of maximum heel-strike braking force, expressed as a percentage of stride (Table 10), was significantly later for the SPEAR than for the MOLLE Extended. This 2% difference did not appear to be related to volume because both the SPEAR, which had a greater volume than the MOLLE Extended, and the MOLLE Standard, which had a lower volume than the MOLLE Extended, produced later times of maximum braking force than did the MOLLE Extended.

Table 10. Time of maximum heel-strike braking force (% stride) while walking at 1.32 m/s, mean (SD)

Load Carriage System		
MOLLE Standard	MOLLE Extended	SPEAR
12.88 [a,b] (1.17)	12.74 [b] (1.29)	13.02 [a] (1.37)

NOTE: Values superscripted with different letters are significantly ($p<0.05$) different

The time of maximum heel-strike lateral force, expressed as a percentage of stride (Table 11), was significantly later for the SPEAR than for the MOLLE Standard. Maximum heel-strike lateral force occurred 26% later for the SPEAR than for the MOLLE Standard. This effect may be volume-related since, as the volume of the pack increased from the MOLLE Standard to the SPEAR, maximum heel-strike lateral force occurred later and later.

Table 11. Time of maximum heel-strike lateral force (% stride) while walking at 1.32 m/s, mean (SD)

Load Carriage System		
MOLLE Standard	MOLLE Extended	SPEAR
3.5 [b] (2.3)	3.9 [a,b] (1.6)	4.4 [a] (1.9)

NOTE: Values superscripted with different letters are significantly ($p<0.05$) different

In contrast to the pattern for braking and lateral force, maximum push-off medial force (Table 12) occurred earlier with the SPEAR than with either MOLLE system, which did not differ significantly from each other. Maximum push-off medial force with the SPEAR occurred about 6% earlier than with the MOLLE systems.

Table 12. Time of maximum push-off medial force (% stride) while walking at 1.32 m/s, mean (SD)

Load Carriage System		
MOLLE Standard	MOLLE Extended	SPEAR
47.42 [a] (4.0)	47.38 [a] (2.9)	44.61 [b] (6.2)

NOTE: Values superscripted with different letters are significantly ($p<0.05$) different

When someone stands still, the force exerted on the feet by the ground is equal to the weight of the body-plus-load. Unweighting is evidenced when vertical ground reaction force drops below the weight of body-plus-load, and results when the body is allowed to accelerate downwards. The extreme case is when the body is allowed to fall freely, and the pressure on the feet goes to zero. Between standing still and falling freely are different degrees of unweighting. The average volunteer carrying a backpack in this study weighed 991 N. Table 13 shows that minimum vertical ground reaction force during the stride were in the neighborhood of 650 N. Thus, the volunteers unweighted to about two-thirds of body-plus-load weight during the stride. The minimum VGRF was significantly higher for the SPEAR than for the MOLLE packs--a difference of about 2.7%. That means that the volunteers allowed the body to accelerate downwards at a greater rate with the MOLLE systems than with the SPEAR. A longer stride may be associated with greater unweighting, because the body tends to drop further with a longer stride. This may account for the difference between the packs in minimum vertical ground reaction force because stride length was shorter with the SPEAR than it was with the MOLLE packs.

Table 13. Minimum vertical ground reaction force (N) while walking at 1.32 m/s, mean (SD)

Load Carriage System		
MOLLE Standard	MOLLE Extended	SPEAR
644.9 [b] (97.2)	646.4 [b] (90.0)	663.0 [a] (104.2)

NOTE: Values superscripted with different letters are significantly ($p<0.05$) different

The time at which minimum vertical ground reaction force occurred (Table 14) was significantly later with the MOLLE Extended than with the MOLLE Standard--a difference of 2.2%. The value for the SPEAR fell between those of the two MOLLEs but did not differ significantly from either of them.

Table 14. Time of minimum vertical ground reaction force (% stride) while walking at 1.32 m/s, mean (SD)

Load Carriage System		
MOLLE Standard	MOLLE Extended	SPEAR
30.84 [b] (2.0)	31.53 [a] (1.8)	31.08 [a,b] (2.2)

NOTE: Values superscripted with different letters are significantly ($p<0.05$) different

Vertical ground reaction moment (Table 15) is caused by the twisting of the boot sole on the surface of the ground (transverse plane). It was significantly (2-3 times) higher for the MOLLE Standard than for either the MOLLE Extended or SPEAR.

Table 15. Maximum vertical ground reaction moment (N•m) while walking at 1.32 m/s, mean (SD)

Load Carriage System		
MOLLE Standard	MOLLE Extended	SPEAR
1.73 [a] (2.44)	0.51 [b] (0.60)	0.76 [b] (1.36)

NOTE: Values superscripted with different letters are significantly ($p<0.05$) different

Maximum ankle angle (Table 16), which indicates the maximum degree of plantarflexion of the foot, was significantly greater for the MOLLE Extended than for the MOLLE Standard, but the difference amounted to only about a half percent. The value for the SPEAR fell between those of the two MOLLEs, but didn't differ significantly from either one. Greater foot plantarflexion is typically associated with a longer stride, but that was not the case here since the MOLLE Standard showed the longest stride but produced the least plantarflexion.

Table 16. Maximum ankle angle (deg) while walking at 1.32 m/s, mean (SD)

Load Carriage System		
MOLLE Standard	MOLLE Extended	SPEAR
135.2 [b] (5.8)	136.0 [a] (5.1)	135.6 [a,b] (5.5)

NOTE: Values superscripted with different letters are significantly ($p<0.05$) different

Ankle range of motion (Table 17) was significantly lower for the MOLLE Standard than for the other pack systems--a difference of about 3%. This is contrary to what would be expected based on the longer stride length evidenced for the MOLLE Standard than for the other two pack systems. However, differences in the position of the ankle at heel-strike could have affected ankle range of motion, independent of stride length.

Table 17. Range of ankle angle (deg) while walking at 1.32 m/s, mean (SD)

Load Carriage System		
MOLLE Standard	MOLLE Extended	SPEAR
32.14 [b] (3.6)	33.20 [a] (2.5)	33.10 [a] (3.2)

NOTE: Values superscripted with different letters are significantly ($p<0.05$) different

Hip flexion-extension angle refers to the sagittal plane angle formed in front of the body between the torso and upper leg. During a stride, the minimum hip flexion-extension angle (Table 18) occurs as the leg reaches forward to contact the ground. It can be made smaller either by reaching the leg further forward as when taking a longer stride, by inclining the trunk further forward, by bending the knee more as the heel contacts the ground, or by any combination of the three. The SPEAR produced a significantly smaller hip minimum flexion-extension angle than the MOLLE Standard--a difference of about a half percent. The value for the MOLLE Extended fell between those of the other two packs, but did not differ significantly from either one. The significantly smaller angle with the SPEAR does not appear to be due to stride length, since the SPEAR produced the shortest stride of the three load carriage systems. Also, Table 25 shows that maximum forward trunk lean cannot account for the differences in minimum hip flexion-extension angle, because the latter variable was the lowest for the SPEAR, but maximum trunk angle (an indicator of maximum forward trunk lean) was the lowest for the SPEAR. Thus, degree of knee bend at heel-strike may have been the determining factor.

Table 18. Minimum hip flexion-extension angle (deg)
while walking at 1.32 m/s, mean (SD)

Load Carriage System		
MOLLE Standard	MOLLE Extended	SPEAR
147.7 [a] (5.77)	147.2 [a,b] (5.60)	146.9 [b] (5.57)

NOTE: Values superscripted with different letters are significantly ($p<0.05$) different

During a stride, the maximum hip flexion-extension angle (Table 19) occurs as the rear leg pushes back against the ground. It can be made larger either by pushing backwards over a greater range as when taking a longer stride, or by inclining the trunk further backwards. The MOLLE Standard produced a significantly greater maximum angle than either of the other two packs--a difference of about a half percent. That could have been related to stride length, since the MOLLE Standard produced the longest stride. However, trunk inclination must have been a factor as well, because the MOLLE Extended, which produced a stride length similar to that of the MOLLE Standard, produced a significantly smaller maximum hip flexion-extension angle. It is likely that, because their centers of mass were located more rearward, the larger two packs (MOLLE Extended and SPEAR) produced greater forward trunk inclination and

concomitantly smaller maximum hip angle. Increased forward trunk inclination is required when the center of mass of the load is further rearward because the load must be brought forward to balance the body-plus-load center of mass over the feet, to keep the walker from falling. This is effected by increased forward lean of the trunk.

Table 19. Maximum hip flexion-extension angle (deg)
while walking at 1.32 m/s, mean (SD)

Load Carriage System		
MOLLE Standard	MOLLE Extended	SPEAR
196.7 [a] (5.7)	195.9 [b] (5.1)	195.6 [b] (5.3)

NOTE: Values superscripted with different letters are significantly ($p<0.05$) different

The time at which maximum hip flexion-extension angle occurred (Table 20) was significantly earlier for the SPEAR than for either of the MOLLE packs--a difference of about 1%.

Table 20. Time of maximum hip flexion-extension angle (% stride)
while walking at 1.32 m/s, mean (SD)

Load Carriage System		
MOLLE Standard	MOLLE Extended	SPEAR
57.92 [a] (1.02)	57.66 [a] (0.97)	57.19 [b] (1.20)

NOTE: Values superscripted with different letters are significantly ($p<0.05$) different

Hip abduction-adduction angle is the angle in a frontal plane between the upper leg and the midline of the body. Greater positive values indicate the hip is more abducted. The maximum hip abduction-adduction angle (Table 21) was significantly greater for the MOLLE Standard than for the other two packs, a difference ranging from 0.8° to 1.3°. This effect may be related to pack volume because, as the packs got larger, the maximum hip abduction-adduction angle decreased.

Table 21. Maximum hip abduction-adduction angle (deg)
while walking at 1.32 m/s, mean (SD)

Load Carriage System		
MOLLE Standard	MOLLE Extended	SPEAR
2.34 [a] (3.07)	1.54 [b] (2.52)	1.05 [b] (2.47)

NOTE: Values superscripted with different letters are significantly ($p<0.05$) different

The time at which maximum hip abduction-adduction angle occurred (Table 22) was significantly later in the gait cycle for the SPEAR than for either of the MOLLE packs--a difference of about 7%-8%. This timing difference was greater and in the opposite direction than the difference for the time at which maximum hip flexion-extension angle occurred.

Table 22. Time at maximum hip abduction-adduction angle (% stride) while walking at 1.32 m/s, mean (SD)

Load Carriage System		
MOLLE Standard	MOLLE Extended	SPEAR
76.3 [b] (12.2)	75.7 [b] (12.1)	81.4 [a] (15.0)

NOTE: Values superscripted with different letters are significantly ($p<0.05$) different

Range of motion for hip abduction-adduction (Table 23) showed the same pattern as for maximum hip abduction-adduction angle, with the MOLLE Standard producing significantly higher values than the other two packs--a difference of 7%-12% amounting to an angular difference of 0.8°-1.3°, the same inter-pack difference as for maximum hip abduction-adduction angle. Apparently, all of the difference in range of hip abduction-adduction angle can be accounted for by differences in maximum hip abduction-adduction angle.

Table 23. Range of hip abduction-adduction angle (deg) while walking at 1.32 m/s, mean (SD)

Load Carriage System		
MOLLE Standard	MOLLE Extended	SPEAR
11.8 [a] (3.4)	11.0 [b] (3.1)	10.5 [b] (2.9)

NOTE: Values superscripted with different letters are significantly ($p<0.05$) different

Trunk angle is defined as the sagittal plane angle in front of the body between the trunk and a vertical line. Minimum trunk angle (Table 24), which represents the most upright position of the trunk during the stride, was significantly greater for the MOLLE Extended than for the other two packs, which did not differ significantly from each other. That means that, in its most upright position, the trunk was inclined forward about a half-degree more with the MOLLE Extended than with the other two packs. That makes sense, as the center of mass of the MOLLE Extended was further behind the subject's back than it was for either of the other two packs, necessitating more forward lean to balance the center of mass over the feet.

Table 24. Minimum trunk angle (deg) while walking at 1.32 m/s, mean (SD)

Load Carriage System		
MOLLE Standard	MOLLE Extended	SPEAR
1.29 [b] (3.15)	1.78 [a] (2.88)	1.33 [b] (2.80)

NOTE: Values superscripted with different letters are significantly ($p<0.05$) different

Maximum trunk angle (Table 25) represents the maximal forward lean of the trunk during the stride. With the MOLLE Extended, the trunk was inclined significantly more forward at its maximum forward lean than with the other two packs--a difference of about a half-degree. Thus, the trunk was inclined further forward with the MOLLE Extended at both its most upright and its most forward leaning position than with the other two packs. Trunk angle range of motion did not differ between the packs. Thus, with the MOLLE Extended, the subjects evidenced greater forward lean throughout the stride.

Table 25. Maximum trunk angle (deg) while walking at 1.32 m/s, mean (SD)

Load Carriage System		
MOLLE Standard	MOLLE Extended	SPEAR
3.99 [b] (2.92)	4.50 [a] (2.89)	3.87 [b] (2.87)

NOTE: Values superscripted with different letters are significantly ($p<0.05$) different

The time at which maximum trunk angle (maximum forward trunk lean) occurred (Table 26) was significantly later for the MOLLE Standard than for the MOLLE Extended. The value for the SPEAR fell between those of the two MOLLEs, but did not differ significantly from either one.

Table 26. Time at maximum trunk angle (% stride)
while walking at 1.32 m/s, mean (SD)

Load Carriage System		
MOLLE Standard	MOLLE Extended	SPEAR
25.8 [a] (23.1)	16.0 [b] (21.3)	20.8 [a,b] (22.1)

NOTE: Values superscripted with different letters are significantly ($p<0.05$) different

Shoulder flexion-extension angle was defined as the sagittal plane angle between the upper arm and trunk, so that when the upper arm was down and in line with the trunk, the angle was 0°. When the arm was rotated behind the trunk, the angle was considered negative, and when the arm was rotated in front of the trunk, the angle

was considered positive. Thus, the minimum shoulder flexion-extension angle (Table 27) represents the peak rearward swing of the arm. It can be seen that there was significantly less rearward swing with the SPEAR than with the two MOLLE packs--a difference of about 4°. It appears that the SPEAR inhibited rearward arm swing. It should be noted that arm swing was also considerably inhibited by the fact that the subjects had to carry a rifle in their hands.

Table 27. Minimum shoulder flexion-extension angle (deg) while walking at 1.32 m/s, mean (SD)

Load Carriage System		
MOLLE Standard	MOLLE Extended	SPEAR
-9.80 [b] (8.9)	-9.83 [b] (6.6)	-5.95 [a] (7.8)

NOTE: Values superscripted with different letters are significantly ($p<0.05$) different

Maximum shoulder flexion-extension angle (Table 28) indicates peak forward swing of the arms. It is interesting to note that, on average, the arms did not swing forward of the trunk at all, as indicated by the negative values in the table for all three packs. The likely reason for this is that the volunteers were holding a rifle in their hands under all three pack conditions, which inhibited the arms from swinging forward. However, given the limited arm swing because of the rifle, both MOLLE packs showed significantly less forward arm swing than did the SPEAR.

Table 28. Maximum shoulder flexion-extension angle (deg) while walking at 1.32 m/s, mean (SD)

Load Carriage System		
MOLLE Standard	MOLLE Extended	SPEAR
-5.21 [b] (8.4)	-5.26 [b] (6.5)	-1.48 [a] (8.9)

NOTE: Values superscripted with different letters are significantly ($p<0.05$) different

The time at which shoulder flexion-extension angle reached maximum (Table 29), or the furthest forward arm swing, occurred later in the stride cycle for the SPEAR than for the MOLLE Extended. The value for the MOLLE Standard fell between those of the other two packs, but did not differ significantly from either one.

Table 29. Time of maximum shoulder flexion-extension angle (% stride) while walking at 1.32 m/s, mean (SD)

Load Carriage System		
MOLLE Standard	MOLLE Extended	SPEAR
64.4 [a,b] (18.9)	60.4 [b] (19.9)	74.2 [a] (26.4)

NOTE: Values superscripted with different letters are significantly ($p<0.05$) different

Shoulder abduction-adduction angle is the frontal plane angle formed by the upper arm and the midline of the body. The minimum shoulder abduction-adduction angle (Table 30) was significantly greater for the SPEAR than for either of the two MOLLE packs--a difference of about 3°, indicating that the arm did not come as close to the trunk with the SPEAR as it did with the MOLLE packs. This could not strictly be a matter of pack width impeding medio-lateral arm movement, because the MOLLE Extended was actually wider than the SPEAR (Table 2).

Table 30. Minimum shoulder abduction-adduction angle (deg) while walking at 1.32 m/s, mean (SD)

Load Carriage System		
MOLLE Standard	MOLLE Extended	SPEAR
18.4 [b] (4.6)	18.0 [b] (3.1)	21.0 [a] (4.7)

NOTE: Values superscripted with different letters are significantly ($p<0.05$) different

Maximum shoulder abduction-adduction angle (Table 31) was also significantly greater with the SPEAR than it was with either of the MOLLE packs--a difference of about 3° as well. Thus, the medio-lateral movement range of the arm did not differ between the SPEAR and the MOLLEs, but the SPEAR caused the movement range to occur further out from the torso.

Table 31. Maximum shoulder abduction-adduction angle (deg) while walking at 1.32 m/s, mean (SD)

Load Carriage System		
MOLLE Standard	MOLLE Extended	SPEAR
21.61 [b] (4.6)	21.41 [b] (2.7)	24.68 [a] (4.5)

NOTE: Values superscripted with different letters are significantly ($p<0.05$) different

Knee flexion-extension torque is defined such that a negative value indicates a muscle torque that acts to flex the knee, and a positive value indicates a muscle torque that tends to extend the knee. Thus, minimum knee flexion-extension torque (Table 32) represents maximum knee flexion torque. The table shows that the SPEAR produced significantly greater peak knee flexion torque than did either of the MOLLE packs--a difference of about 15%, which cannot be accounted for by pack weight, since the SPEAR weighed only 2%-3% more than the MOLLEs. It may bear some relationship to the shorter stride length with the SPEAR.

Table 32. Minimum knee flexion-extension torque (N•m) while walking at 1.32 m/s, mean (SD)

Load Carriage System		
MOLLE Standard	MOLLE Extended	SPEAR
-30.4 [a] (9.4)	-29.5 [a] (8.8)	-34.4 [b] (12.3)

NOTE: Values superscripted with different letters are significantly ($p<0.05$) different

The time at which minimum hip flexion-extension torque occurred (Table 33), that is the time of maximum hip flexion torque, was later for the SPEAR, in terms of percentage of stride, than for the MOLLE Standard--a difference of about 5%. The value for the MOLLE Extended fell between those for the other two packs, but did not differ significantly from either one.

Table 33. Time of minimum hip flexion-extension torque (% stride) while walking at 1.32 m/s, mean (SD)

Load Carriage System		
MOLLE Standard	MOLLE Extended	SPEAR
84.5 [b] (13.3)	85.3 [a,b] (14.6)	88.6 [a] (16.2)

NOTE: Values superscripted with different letters are significantly ($p<0.05$) different

Hip flexion-extension torque (Table 34) was calculated such that a positive value represented hip flexion torque, while a negative value indicated hip extension torque. Thus, the peak value of this variable represented maximum hip flexion torque. The table shows that the SPEAR produced significantly greater peak hip flexion torque than did the MOLLE Extended--a difference of about 18%, which cannot be accounted for by pack weight, since the SPEAR weighed only 2.4% more than the MOLLE Extended. The value for the MOLLE Standard fell between those for the other two packs, but did not differ significantly from either one.

Table 34. Maximum hip flexion-extension torque (N•m)
while walking at 1.32 m/s, mean (SD)

Load Carriage System		
MOLLE Standard	MOLLE Extended	SPEAR
38.4 ^{a,b} (15.7)	34.6 ^{b} (14.8)	40.8 ^{a} (23.7)

NOTE: Values superscripted with different letters are significantly ($p<0.05$) different)

Maximum hip flexion-extension torque occurred significantly earlier (Table 35) with the SPEAR, as percentage of stride, than it did with the MOLLE Standard--a difference of about 5%. The value for the MOLLE Extended fell between those of the other two packs, but did not differ significantly from either one.

Table 35. Time of maximum hip flexion-extension torque (% stride)
while walking at 1.32 m/s, mean (SD)

Load Carriage System		
MOLLE Standard	MOLLE Extended	SPEAR
71.5 ^{a} (10.5)	70.1 ^{a,b} (9.2)	67.8 ^{b} (4.4)

NOTE: Values superscripted with different letters are significantly ($p<0.05$) different

The time at which the center of mass reached its maximum vertical position (Table 36) was significantly later, as percentage of stride, for the SPEAR than for the MOLLE Extended. The value for the MOLLE Standard fell in between those of the other two packs, but did not differ significantly from either one.

Table 36. Time of maximum center of mass vertical position (% stride)
while walking at 1.32 m/s, mean (SD)

Load Carriage System		
MOLLE Standard	MOLLE Extended	SPEAR
59.5 ^{a,b} (25.6)	66.6 ^{a} (24.5)	54.2 ^{b} (24.8)

NOTE: Values superscripted with different letters are significantly ($p<0.05$) different

Minimum center of mass vertical velocity (Table 37) was significantly less negative for the SPEAR than for the two MOLLE packs. That means the peak downward velocity of the center of mass was less for the SPEAR than for the MOLLE packs--a difference of 3%-5%. This is in accordance with the greater unweighting that occurs with the MOLLE (Table 13); "greater unweighting" means greater downward acceleration, usually associated with greater downward velocity.

Table 37. Minimum center of mass vertical velocity (m/s) while walking at 1.32 m/s, mean (SD)

Load Carriage System		
MOLLE Standard	MOLLE Extended	SPEAR
-0.283 [b] (0.044)	-0.277 [b] (0.029)	-0.269 [a] (0.036)

NOTE: Values superscripted with different letters are significantly ($p<0.05$) different

The time at which maximum center of mass vertical velocity occurred (Table 38) was significantly later for the MOLLE Standard than for the MOLLE Extended. The value for the SPEAR fell between those of the other two packs, and closer to that of the MOLLE Extended, but did not differ significantly from either one.

Table 38. Time of maximum center of mass vertical velocity (% stride) while walking at 1.32 m/s, mean (SD)

Load Carriage System		
MOLLE Standard	MOLLE Extended	SPEAR
96.7 [a] (23.4)	83.3 [b] (24.9)	87.1 [a,b] (28.8)

NOTE: Values superscripted with different letters are significantly ($p<0.05$) different

What is normally referred to as constant speed walking actually consists of repeated cycles of deceleration-acceleration due to the braking force at heel-strike and the propulsive force at push-off. The minimum center of mass horizontal velocity (Table 39) with the SPEAR was significantly lower than with either MOLLE--a difference of 2%-3%. Thus, during the normal horizontal acceleration and deceleration of the stride, the walker slowed more with the SPEAR than with the MOLLE packs. However, since average walking speed was the same for all packs tested (within 5% of 1.32 m/s), volunteers must have made up for the low minimum speed by moving faster elsewhere in the stride.

Table 39. Minimum center of mass horizontal velocity (m/s) while walking at 1.32 m/s, mean (SD)

Load Carriage System		
MOLLE Standard	MOLLE Extended	SPEAR
1.228 [a] (0.0567)	1.216 [a] (0.056)	1.196 [b] (0.048)

NOTE: Values superscripted with different letters are significantly ($p<0.05$) different

The time at which the center of mass vertical acceleration reached a minimum (Table 40) was significantly earlier for the SPEAR than for the MOLLE Standard--a difference of about 12%-15%. The value for the MOLLE Extended fell between those for the other two packs, and closer to that for the MOLLE Standard, but did not differ significantly from that of either one.

Table 40. Time of minimum center of mass vertical acceleration (% stride) while walking at 1.32 m/s, mean (SD)

Load Carriage System		
MOLLE Standard	MOLLE Extended	SPEAR
77.2 [a] (17.8)	74.0 [a,b] (21.3)	65.4 [b] (24.5)

NOTE: Values superscripted with different letters are significantly ($p<0.05$) different

The maximum center of mass anterior-posterior acceleration (Table 41) was significantly higher for the MOLLE Extended than for the SPEAR--a difference of about 8%. The value for the MOLLE Standard fell between those for the other two packs, although considerably closer to that of the SPEAR, but did not differ significantly from either one.

Table 41. Maximum center of mass anterior-posterior acceleration (m/s^2) while walking at 1.32 m/s, mean (SD)

Load Carriage System		
MOLLE Standard	MOLLE Extended	SPEAR
2.49 [a,b] (0.38)	2.68 [a] (0.66)	2.41 [b] (0.42)

NOTE: Values superscripted with different letters are significantly ($p<0.05$) different

During a normal walking stride, mediolateral force changes in direction from medially directed to laterally directed. The time at which this occurred (Table 42) was significantly later for the MOLLE Standard than for the MOLLE Extended--a difference of about 18%. The value for the SPEAR fell between those for the other two packs, but did not differ significantly from either one.

Table 42. Time of 1st direction change in mediolateral force (% stride) while walking at 1.32 m/s, mean (SD)

Load Carriage System		
MOLLE Standard	MOLLE Extended	SPEAR
7.58 [a] (2.11)	6.44 [b] (2.73)	7.12 [a,b] (3.03)

NOTE: Values superscripted with different letters are significantly ($p<0.05$) different

There is normally a second change in the direction of medio-lateral ground-reaction force later in the stride. Just as the foot pushes off the ground, the force usually becomes medially directed. The time of this force direction change, expressed as a percentage of stride (Table 43), occurred significantly later for the MOLLE Standard than for the other two packs--a difference of about 19%-22%.

Table 43. Time of 2nd direction change in mediolateral force (% stride) while walking at 1.32 m/s, mean (SD)

Load Carriage System		
MOLLE Standard	MOLLE Extended	SPEAR
75.8 [a] (25.1)	61.9 [b] (33.1)	63.5 [b] (32.9)

NOTE: Values superscripted with different letters are significantly ($p<0.05$) different

EFFECTS OF PACK SHAPE AND VOLUME ON RUNNING BIOMECHANICS

Despite the fact that both represent bi-pedal human locomotion, running differs considerably from walking. Running consists of both a single-support phase in which one foot is on the ground and a flight phase in which neither foot is on the ground. Walking has no flight phase, but has a double-support phase in which both feet are on the ground, as well as a single-support phase in which one foot is on the ground. In addition, the running stride is generally longer than the walking stride, and the ground impact forces are greater. The running biomechanics results shown in this section depict variables for which at least two of the packs differed significantly.

Impulse is the product of force and time. Medial impulse over the entire stride (Table 44) was significantly lower for the SPEAR than for the two MOLLE packs--a difference of about 23%-34%. This is despite the fact that the SPEAR was 3.4% heavier than the MOLLEs.

Table 44. Medial impulse over entire stride (N•s) while running at 2.91 m/s, mean (SD)

Load Carriage System		
MOLLE Standard	MOLLE Extended	SPEAR
13.2 [b] (6.9)	14.5 [b] (5.7)	10.2 [a] (6.8)

NOTE: Values superscripted with different letters are significantly ($p<0.05$) different

In keeping with the results for medial impulse, the SPEAR produced significantly lower average medial force than did the MOLLE packs (Table 45)--a difference of about 22%-29%. The results of impulse and force correspond unless stride time differs.

Table 45. Average medial force over entire stride (N) while running at 2.91 m/s, mean (SD)

Load Carriage System		
MOLLE Standard	MOLLE Extended	SPEAR
17.0 [b] (9.0)	18.7 [b] (7.6)	13.3 [a] (9.0)

NOTE: Values superscripted with different letters are significantly ($p<0.05$) different

Because the SPEAR was heavier than the MOLLEs, correction of average medial force for the weight carried heightened the difference between the SPEAR and MOLLEs. Average medial force over entire stride divided by loaded subject weight (Table 46) was significantly lower for the SPEAR than the MOLLEs--a difference of about 23%-32%.

Table 46. Average medial force (N) over entire stride divided by loaded subject weight while running at 2.91 m/s, mean (SD)

Load Carriage System		
MOLLE Standard	MOLLE Extended	SPEAR
0.017 [b] (0.010)	0.019 [b] (0.008)	0.013 [a] (0.009)

NOTE: Values superscripted with different letters are significantly ($p<0.05$) different

Just as for average medial force over the entire stride, maximum push-off medial force (Table 47) was significantly lower for the SPEAR than for either of the MOLLE packs--a difference of 18%-27%. This is despite the fact that the SPEAR weighed 3.4% more than the MOLLEs. A similar effect was seen when force was normalized for loaded subject weight (Table 48).

Table 47. Maximum push-off medial force (N) while running at 2.91 m/s, mean (SD)

Load Carriage System		
MOLLE Standard	MOLLE Extended	SPEAR
94.6 [b] (39.9)	105.9 [b] (32.9)	77.2 [a] (45.4)

NOTE: Values superscripted with different letters are significantly ($p<0.05$) different

Table 48. Maximum push-off medial force (N) divided by loaded subject weight while running at 2.91 m/s, mean (SD)

Load Carriage System		
MOLLE Standard	MOLLE Extended	SPEAR
0.096 [b] (0.042)	0.107 [b] (0.034)	0.078 [a] (0.045)

NOTE: Values superscripted with different letters are significantly ($p<0.05$) different

In contrast to the medial impulse results, lateral impulse over entire stride (Table 49) was significantly higher for the SPEAR than for the MOLLE Extended--a difference of 124%. The value for the MOLLE Standard fell between those for the other two packs, but did not differ significantly from either one.

Table 49. Lateral impulse over entire stride (N•s) while running at 2.91 m/s, mean (SD)

Load Carriage System		
MOLLE Standard	MOLLE Extended	SPEAR
1.57 [a,b] (2.1)	1.21 [b] (1.8)	2.71 [a] (5.3)

NOTE: Values superscripted with different letters are significantly ($p<0.05$) different

The results of average lateral force over entire stride (Table 50) were in keeping with those for lateral impulse, with the SPEAR significantly higher than the MOLLE Extended--a difference of about 127%. The value for the MOLLE Standard fell between those for the other two packs, and closer to that of the MOLLE Extended, but did not differ significantly from either one. A similar relationship was evidenced when force was adjusted for load (Table 51).

Table 50. Average lateral force over entire stride (N) while running at 2.91 m/s, mean (SD)

Load Carriage System		
MOLLE Standard	MOLLE Extended	SPEAR
2.0 [a,b] (2.7)	1.5 [b] (2.2)	3.4 [a] (6.7)

NOTE: Values superscripted with different letters are significantly ($p<0.05$) different

Table 51. Average lateral force over entire stride (N) divided by loaded subject weight while running at 2.91 m/s, mean (SD)

Load Carriage System		
MOLLE Standard	MOLLE Extended	SPEAR
0.002 [a,b] (0.003)	0.001 [b] (0.002)	0.003 [a] (0.006)

NOTE: Values superscripted with different letters are significantly ($p<0.05$) different

In keeping with the results for average lateral force over the entire stride, maximum heel-strike lateral force (Table 52) was significantly higher with the SPEAR than with either MOLLE pack--a difference of about 40%-70%. A similar relationship was seen when the forces were normalized for loaded subject weight (Table 53).

Table 52. Maximum heel-strike lateral force (N) while running at 2.91 m/s, mean (SD)

Load Carriage System		
MOLLE Standard	MOLLE Extended	SPEAR
30.0 [b] (33.2)	23.8 [b] (34.4)	42.2 [a] (55.8)

NOTE: Values superscripted with different letters are significantly ($p<0.05$) different

Table 53. Maximum heel-strike lateral force (N) divided by loaded subject weight while running at 2.91 m/s, mean (SD)

Load Carriage System		
MOLLE Standard	MOLLE Extended	SPEAR
0.03 [b] (0.031)	0.02 [b] (0.031)	0.04 [a] (0.049)

NOTE: Values superscripted with different letters are significantly ($p<0.05$) different

Maximum heel-strike vertical ground reaction force (Table 54) is one of the most important variables in gait analysis because of the presumption that greater impact force increases risk of injury. For this measure, the MOLLE Extended was significantly higher than the SPEAR--a difference of about 1.7%. That was despite the fact that the SPEAR weighed 3.4% more than the MOLLE Extended. Vertical force for the MOLLE Standard, although close to that of the SPEAR, fell between those for the other two packs, but did not differ significantly from either one.

Table 54. Maximum heel-strike vertical ground reaction force (N) while running at 2.91 m/s, mean (SD)

Load Carriage System		
MOLLE Standard	MOLLE Extended	SPEAR
2083.1 [a,b] (269.9)	2116.4 [a] (258.4)	2080.2 [b] (263.5)

NOTE: Values superscripted with different letters are significantly ($p<0.05$) different

Minimum ankle angle (Table 55), an indicator of the extent of foot dorsiflexion, was significantly higher with the MOLLE Standard than with the MOLLE Extended or SPEAR--a difference of about 1%. Thus, there was less dorsiflexion with the MOLLE Standard than with the other two packs.

Table 55. Minimum ankle angle (deg) while running at 2.91 m/s, mean (SD)

Load Carriage System		
MOLLE Standard	MOLLE Extended	SPEAR
89.40 [a] (4.58)	88.56 [b] (4.12)	88.44 [b] (4.56)

NOTE: Values superscripted with different letters are significantly ($p<0.05$) different

Running gait with the MOLLE Standard was characterized by less total range of ankle motion than was the MOLLE Extended (Table 56)--a difference of about 3%. This was in keeping with lower peak dorsiflexion shown with the MOLLE Extended. The value for the SPEAR fell right in-between those for the other two packs, but did not differ significantly from either one.

Table 56. Range of ankle angle (deg) while running at 2.91 m/s, mean (SD)

Load Carriage System		
MOLLE Standard	MOLLE Extended	SPEAR
49.3 [b] (4.0)	50.7 [a] (4.2)	50.0 [a,b] (4.7)

NOTE: Values superscripted with different letters are significantly ($p<0.05$) different

Maximum knee angle (Table 57) indicates the degree to which the knee is straightened, with 180° signifying a fully straightened leg. During the load carriage trials, the volunteers did not come close to full knee extension. However, the knee became significantly straighter with the MOLLE Standard than with the MOLLE Extended, by about 1.4°. The value for the SPEAR fell between those for the other two packs, but did not differ significantly from either one.

Table 57. Maximum knee angle (deg) while running at 2.91 m/s, mean (SD)

Load Carriage System		
MOLLE Standard	MOLLE Extended	SPEAR
168.67 [a] (3.85)	167.30 [b] (3.64)	168.42 [a,b] (4.15)

NOTE: Values superscripted with different letters are significantly ($p<0.05$) different

Since hip flexion-extension angle was measured ventrally, a greater angle indicated more hip extension. Maximum hip flexion-extension angle (Table 58) was significantly higher for the MOLLE Extended than for the MOLLE Standard--a difference of a bit over 1°. The value for the SPEAR fell between those for the other two packs, and closer to that of the MOLLE Extended, but did not differ significantly from either one.

Table 58. Maximum hip flexion-extension angle (deg)
while running at 2.91 m/s, mean (SD)

Load Carriage System		
MOLLE Standard	MOLLE Extended	SPEAR
190.9 [b] (3.6)	192.2 [a] (5.0)	191.8 [a,b] (4.5)

NOTE: Values superscripted with different letters are significantly ($p<0.05$) different

A greater trunk angle indicates more forward trunk lean. Maximum trunk angle (Table 59) was significantly less for the SPEAR than for the MOLLEs, indicating about 1° less forward trunk lean with the SPEAR. This is to be expected because the SPEAR's center of mass was closer to the back than that of the MOLLE, requiring less forward lean to balance the center of mass over the feet to prevent falling.

Table 59. Maximum trunk angle (deg) while running at 2.91 m/s, mean (SD)

Load Carriage System		
MOLLE Standard	MOLLE Extended	SPEAR
12.7 [a] (3.14)	12.1 [a] (3.75)	11.2 [b] (3.78)

NOTE: Values superscripted with different letters are significantly ($p<0.05$) different

The range of trunk angle (Table 60), an indicator of sagittal plane forward-backward sway of the trunk, differed significantly among all three packs, with MOLLE Standard the highest, the MOLLE Extended second, and the SPEAR the lowest. This may be related to moment of inertia, which is the resistance an object offers to being rotated. Moment of inertia is quantified as the square of the distance from the pivot point to the object's center of mass times the mass, plus the object's moment of inertia

about its own center of mass. Assuming uniform distribution of the load within a pack, the latter is greater when pack volume is greater. The SPEAR, being the tallest and most voluminous of the packs, likely had the greatest moment of inertia, which provided the greatest resistance to rotation and thus, the least trunk rotation. The MOLLE Extended, which has the second most volume, produced the second lowest degree of trunk sway.

Table 60. Range of trunk angle (deg) while running at 2.91 m/s, mean (SD)

Load Carriage System		
MOLLE Standard	MOLLE Extended	SPEAR
5.27 [a] (2.03)	4.57 [b] (1.68)	3.95 [c] (1.41)

NOTE: Values superscripted with different letters are significantly ($p<0.05$) different

Minimum shoulder flexion-extension angle (Table 61), an indicator of the degree of shoulder extension (rearward swing), was another variable which differed significantly among all three packs, with the MOLLE Standard showing the greatest shoulder extension, the MOLLE Extended showing the second most shoulder extension, and the SPEAR showing the least shoulder extension. The arm swung backwards about 3° further with the MOLLE Extended than with the SPEAR, and about 4.5° further backwards with the MOLLE Standard than with the MOLLE Extended. The difference between the two MOLLEs was greater than that observed during walking. Pack volume might have been a factor, as the most voluminous pack (the SPEAR) showed the least shoulder extension, while the least voluminous pack (MOLLE Standard) showed the most shoulder extension. All three packs showed greater shoulder extension during running than during walking.

Table 61. Minimum shoulder flexion-extension angle (deg)
while running at 2.91 m/s, mean (SD)

Load Carriage System		
MOLLE Standard	MOLLE Extended	SPEAR
-19.1 [c] (8.8)	-14.6 [b] (8.4)	-11.4 [a] (10.4)

NOTE: Values superscripted with different letters are significantly ($p<0.05$) different

Maximum shoulder flexion-extension angle (Table 62), an indicator of the degree of shoulder flexion (forward swing), was significantly greater for the SPEAR than for either MOLLE pack. On average, the arm swung forward of the trunk about 3° with the SPEAR, but did not swing forward of the trunk at all with the MOLLE. The fact that the volunteers were carrying rifles was the main impediment to forward arm swing.

Table 62. Maximum shoulder flexion-extension angle (deg)
while running at 2.91 m/s, mean (SD)

Load Carriage System		
MOLLE Standard	MOLLE Extended	SPEAR
-1.45 [b] (11.70)	-0.34 [b] (9.01)	3.12 [a] (11.56)

NOTE: Values superscripted with different letters are significantly ($p<0.05$) different

The greater forward arm swing with the SPEAR somewhat made up for its lesser rearward arm swing. Thus, total arm swing range (Table 63) did not differ between the MOLLE Extended and the SPEAR. Nevertheless, the MOLLE Standard showed a significantly greater arm swing range than either the MOLLE Extended or the SPEAR--a difference of about 3°. Thus, the pack with the least volume was associated with the most arm swing.

Table 63. Range of shoulder flexion-extension angle (deg)
while running at 2.91 m/s, mean (SD)

Load Carriage System		
MOLLE Standard	MOLLE Extended	SPEAR
17.6 [a] (9.7)	14.2 [b] (7.7)	14.5 [b] (9.0)

NOTE: Values superscripted with different letters are significantly ($p<0.05$) different

Shoulder abduction-adduction angle is a measure of the frontal plane angle between trunk and upper arm, and shows the lateral excursion of the upper arm relative to the trunk. Table 64 shows that the arm came significantly closer to the trunk with the MOLLE Standard than with the MOLLE Extended--a difference of about 2°. The value for the SPEAR fell between those for the other two packs, but did not differ significantly from either one. Pack width was likely a factor, as the MOLLE Standard was the narrowest and the MOLLE Extended the widest pack.

Table 64. Minimum shoulder abduction-adduction angle (deg)
while running at 2.91 m/s, mean (SD)

Load Carriage System		
MOLLE Standard	MOLLE Extended	SPEAR
19.0 [b] (6.4)	20.9 [a] (6.0)	20.3 [a,b] (5.1)

NOTE: Values superscripted with different letters are significantly ($p<0.05$) different

Table 65, which depicts maximum shoulder abduction-adduction angle, a measure of how far laterally from the trunk the upper arm rotates, shows significantly

less lateral rotation with the MOLLE Standard than with the MOLLE Extended or SPEAR--a difference of about 2°. Again, this was likely due to the fact that the MOLLE Standard was the narrowest of the three packs. With both minimum and maximum angles closer to the body, the MOLLE Standard produced an arm swing range similar to that of the other packs, but closer to the body.

Table 65. Maximum shoulder abduction-adduction angle (deg) while running at 2.91 m/s, mean (SD)

Load Carriage System		
MOLLE Standard	MOLLE Extended	SPEAR
27.8 [b] (6.0)	29.4 [a] (5.8)	29.3 [a] (4.5)

NOTE: Values superscripted with different letters are significantly ($p<0.05$) different

Maximum hip flexion-extension torque during running (Table 66) is a measure of the peak torque exerted while pushing the foot rearward along the ground. This force was significantly lower for the SPEAR than for the MOLLE Extended--a difference of about 15%. The value for the MOLLE Standard fell between those for the other two packs, and much closer to that of the MOLLE Extended, but did not differ significantly from either one.

Table 66. Maximum hip flexion-extension torque (N•m) while running at 2.91 m/s, mean (SD)

Load Carriage System		
MOLLE Standard	MOLLE Extended	SPEAR
171.1 [a,b] (62.9)	173.1 [a] (63.0)	146.9 [b] (59.1)

NOTE: Values superscripted with different letters are significantly ($p<0.05$) different

The center of mass of the body reached a significantly lower position (Table 67) with the MOLLE packs than with the SPEAR, in the neighborhood of half a centimeter lower. This was in keeping with the higher center of mass of the SPEAR pack. Because the packs were relatively light, the higher center of mass of the SPEAR did not have as great an impact on body-plus-load center of mass as would a much heavier pack.

Table 67. Minimum center of mass vertical position (m)
while running at 2.91 m/s, mean (SD)

Load Carriage System		
MOLLE Standard	MOLLE Extended	SPEAR
0.951 [b] (0.049)	0.951 [b] (0.046)	0.956 [a] (0.045)

NOTE: Values superscripted with different letters are significantly ($p<0.05$) different

Just as its low position was higher than those of the MOLLEs, the SPEAR's highest center of mass position (Table 68) was significantly higher than those of the MOLLEs. The difference was not quite as great as for the center of mass low point, amounting to only about a third of a centimeter.

Table 68. Maximum center of mass vertical position (m)
while running at 2.91 m/s, mean (SD)

Load Carriage System		
MOLLE Standard	MOLLE Extended	SPEAR
1.047 [b] (0.056)	1.048 [b] (0.053)	1.051 [a] (0.051)

NOTE: Values superscripted with different letters are significantly ($p<0.05$) different

The MOLLE Extended pack reached a significantly greater vertical (upward) velocity during running (Table 69) than did the MOLLE Standard--a difference of about 3%. The value for the SPEAR fell between those for the other two packs, but did not differ significantly from either one.

Table 69. Maximum center of mass vertical velocity (m/s)
while running at 2.91 m/s, mean (SD)

Load Carriage System		
MOLLE Standard	MOLLE Extended	SPEAR
0.72 [b] (0.10)	0.74 [a] (0.12)	0.73 [a,b] (0.09)

NOTE: Values superscripted with different letters are significantly ($p<0.05$) different

Based on the sign conventions used in the analysis, positive anterior-posterior acceleration refers to acceleration in the forward direction. When the volunteers ran with the SPEAR, there was greater peak anterior-posterior acceleration of the body-plus-pack (Table 70) than when they ran with the MOLLE packs--a difference of 27%-34%. That could be a function of shoulder strap tightness. A pack attached to the user by firm, tight shoulder straps accelerates forward as the user accelerates, while a looser strap allows the pack to lag the user, lessening forward pack acceleration. On the other

hand, a very loose strap can suddenly accelerate the pack when the strap becomes taut, producing high pack acceleration. Thus, higher pack acceleration can be due to either firm or loose straps. The analysis did not differentiate between these two possibilities.

Table 70. Maximum center of mass anterior-posterior acceleration (m/s^2) while running at 2.91 m/s, mean (SD)

Load Carriage System		
MOLLE Standard	MOLLE Extended	SPEAR
5.6 [b] (2.06)	5.3 [b] (2.09)	7.1 [a] (2.43)

NOTE: Values superscripted with different letters are significantly ($p<0.05$) different

SUMMARY TABLES

To facilitate drawing conclusions from the great number of variables showing significant differences between pack conditions, tables were constructed to summarize the most important findings. Table 71 shows notable kinematic variables (angular and linear position, velocity, acceleration), while Table 72 shows notable kinetic variables (force, torque, and impulse). Rather than means, which are in the individual tables throughout the Results section, the summary tables contain symbols to show which pack systems differed significantly and in what direction they differed.

Table 71. Notable kinematic variables showing significant differences between packs

Variable	WALKING			RUNNING		
	MOLLE	MOLLE EXTENDED	SPEAR	MOLLE	MOLLE EXTENDED	SPEAR
stride length	↑	-	↓			
minimum trunk angle	↓	↑	↓			
maximum trunk angle	↓	↑	↓	↑	↑	↓
trunk angle range				↑	↔	↓
minimum shoulder flexion-extension angle	↓	↓	↑	↓	↔	↑
maximum shoulder flexion-extension angle	↓	↓	↑	↓	↓	↑
shoulder flexion-extension angle range				↑	↓	↓
minimum shoulder abduction-adduction angle	↓	↓	↑	↓	↑	-
maximum shoulder abduction-adduction angle	↓	↓	↑	↓	↑	↑
minimum center of mass vertical position				↓	↓	↑
maximum center of mass vertical position				↓	↓	↑
minimum center of mass vertical velocity	↓	↓	↑			
maximum center of mass vertical velocity				↓	↑	-
minimum center of mass horizontal velocity	↑	↑	↓			
maximum center of mass anterior-posterior acceleration	-	↑	↓	↓	↓	↑
ankle angle range				↓	↑	-
maximum knee angle				↑	↓	-
maximum hip flexion-extension angle	↑	↓	↓	↓	↑	-

(↑):a significantly higher mean; (↓):a significantly lower mean; (-) a mean not significantly different from the others
(↔):a mean significantly lower than the higher mean and significantly higher than the lower mean.

Table 72. Notable kinetic variables showing significant differences between packs

Variable	WALKING			RUNNING		
	MOLLE	MOLLE EXTENDED	SPEAR	MOLLE	MOLLE EXTENDED	SPEAR
maximum braking force divided by loaded subject weight	↑	↓	↓			
maximum ankle force divided by loaded subject weight	↑	-	↓			
maximum knee force divided by loaded subject weight	↑	-	↓			
minimum vertical force	↓	↓	↑			
maximum ground reaction moment	↑	↓	↓			
minimum knee flexion-extension torque	↑	↑	↓			
maximum hip flexion-extension torque	-	↓	↑	-	↑	↓
medial impulse				↑	↑	↓
average medial force				↑	↑	↓
average medial force divided by loaded subject weight				↑	↑	↓
maximum push-off medial force				↑	↑	↓
max push-off medial force divided by loaded subject weight				↑	↑	↓
maximum vertical ground reaction force				-	↑	↓

(↑):a significantly higher mean; (↓):a significantly lower mean; (-) a mean not significantly different from the others
(↔):a mean significantly lower than the higher mean and significantly higher than the lower mean.

DISCUSSION

Table 73 summarizes the characteristics of the pack systems tested and serves to help identify the reasons for some of the differential effects of the packs on walking and running gait.

Table 73. Pack sizes and shapes

	Pack System		
Dimension	**MOLLE Standard**	**MOLLE Extended**	**SPEAR**
width (medio-lateral)	medium	high	high
height above belt	medium	medium	high
depth (anterior-posterior)	medium	high	medium
COM distance behind back	medium	high	low
impediment to rearward elbow movement	low	medium	high

COM = center of mass

KINEMATICS OF LOCOMOTION

The SPEAR's impediment to rearward arm movement may have contributed to the shorter walking stride length evidenced with it than with either MOLLE. The arms swung about 4° further back with the MOLLE packs than with the SPEAR. Allowing the arms to swing freely helps counteract the tendency for the body to twist as horizontal force is alternately exerted on the ground by the two feet. With less impediment to rearward arm swing, it is easier to take a longer stride. This may not be a critical issue as pack weight increases, because stride length normally decreases with increasing load anyway (29). Also, when the moment of inertia of the upper body increases by adding a pack, both the degree of trunk transverse-plane rotation and stride length decrease (26). This is because the transverse plane angular momentum (moment of inertia times angular velocity) imparted to the body via the off-center push-off force of the foot is accounted for to a greater degree by the rotational inertia (moment of inertia) of the pack-plus-trunk and less by its angular velocity. Taking these facts into consideration, the impediment to rearward arm swing of the wider packs may detract from the soldier's ability to take a longer walking stride with a lighter load, but may not interfere with normal stride length while carrying heavier loads. The total range of arm swing was not affected by the pack during walking because, while the arms did not swing back as much with the SPEAR as with the MOLLEs, they swung further forward with the SPEAR, making total arm swing about equal for all packs. Despite similarity in total range of motion with the different packs, inhibition of rearward arm swing by lateral protrusion of the SPEAR may have contributed to the shorter stride length.

It is important to note that the pack effect on stride length held only for walking but not running, even though the effect of pack width on arm swing was similar for running and walking. For running as for walking, the arms did not swing as far back with the SPEAR as with the MOLLE packs. However, in contrast to the pattern for walking, total arm swing range during running was less with the two wider packs (MOLLE Extended and SPEAR) than it was for the narrower one (MOLLE Standard). The fact that stride length was not affected by pack width or arm swing during running may be explained by the fact that the arms were held further out to the sides of the body with the wider packs, engendering an increase in transverse-plane moment of inertia without increased arm swing (moment of inertia is proportional to mass times the square of the distance from the rotational axis, so that the distance has great influence). It must be remembered that the trials were conducted while the volunteers were carrying rifles in their hands. While this tended to inhibit arm swing, the volunteers still produced a fairly wide range of arm swing while running.

The greater forward trunk inclination that volunteers exhibited while walking with the MOLLE Extended than with either the MOLLE Standard or SPEAR was most likely caused by the fact that the center of mass of the MOLLE Extended was located much further behind the back than were the centers of mass of the other two packs. This necessitated increased forward trunk lean with the MOLLE Extended to keep the center of mass of body-plus-pack over the feet, thereby maintaining balance.

The relationship between packs as to forward trunk inclination was not quite the same in running as in walking. While during walking the trunk was inclined further forward with the MOLLE Extended than with either the MOLLE Standard or SPEAR, during running both MOLLEs produced similar amounts of maximum forward trunk inclination, both greater than that of the SPEAR. The common characteristics of the MOLLE packs relative to the SPEAR (shorter pack height and pack center-of-mass further from the back) may account for their similar effect on forward trunk inclination during running, but it is difficult to tell why the MOLLE Standard did not show the same effect during walking. Another difference between the walking and running effects on trunk angle was that pack-type had a significant effect on minimum trunk angle (most upright trunk position) during walking but not during running. The reason that trunk angle appears less related to the pack center of mass location in running than in walking is likely related to the fact that at least one foot is always on the ground during walking but not during running. There is no base of support over which it is necessary to maintain balance during the airborne phase of running.

Trunk angle range was affected by pack-type during running but not walking. Sagittal plane trunk range of motion was greatest for the MOLLE Standard and least for the SPEAR. This may relate to pack shape. The SPEAR was the highest pack, giving it the greatest moment of inertia about the hips. For a given amount of torque exerted on the trunk, a greater moment of inertia would cause less angular acceleration and thus less range of trunk motion. Differences between walking and running mechanics likely account for the differences in pack effects on sagittal plane trunk movement. One clear

difference between walking and running was that the trunk reached a much more forward-leaning position in running (11°-13°) than in walking (4°-5°). In addition, running is more dynamic than walking, being characterized by higher velocities and accelerations. During about 30% of walking stride, body weight is supported on both feet, while the body is never supported on both feet during running. In the airborne phase of running, neither foot is on the ground.

The pack systems showed different effects on shoulder abduction-adduction angle (the degree to which the arms were held laterally away from the trunk) during walking than during running. During walking, both MOLLEs evinced significantly lower minimum and maximum shoulder abduction-adduction angles than the SPEAR. However, during running, while the MOLLE Standard again produced lower angles than the SPEAR, the angles for the MOLLE Extended were close to that of the SPEAR. In comparison to walking, running produced a similar minimum shoulder abduction-adduction angle, but a considerably larger maximum shoulder abduction-adduction angle, especially for the MOLLE Extended pack.

During walking, there was no significant pack effect on either minimum or maximum center of mass vertical position. However, during running both MOLLE packs produced lower center of mass minimum and maximum vertical positions, meaning that the body was lower throughout the stride. That may be attributable to pack shape. Forward lean of the trunk brings the center of mass of the trunk, and thus of the whole body, lower. Since the SPEAR's center of mass was closer to the back, it did not require as much forward trunk lean to get the center of mass of body-plus-pack over the feet, thereby keeping the center of mass higher. This interpretation is supported by the significantly greater forward trunk lean when the volunteers carried the MOLLEs rather than the SPEAR during running. Yet there is no obvious reason why these differences among the packs appeared during running but not during walking.

KINETICS OF LOCOMOTION

The fact that braking force divided by loaded subject weight during walking was the highest for the MOLLE Standard pack was likely related to the longer stride length of volunteers walking with that pack. A longer walking stride length often means that the foot is placed more forward of the body, a maneuver usually associated with greater braking force. This effect was apparently transmitted up the leg, as indicated by the relatively high ankle and knee forces for the MOLLE Standard as compared to the MOLLE Extended and SPEAR, even after normalization for loaded subject weight.

Minimum vertical ground reaction force was lower for the MOLLEs than for the SPEAR. With less vertical ground reaction force to counter bodyweight, more of the bodyweight can act to accelerate the body downwards. That means the body was allowed to drop more freely with the MOLLEs. This difference could have been related to the shorter walking stride length with the SPEAR. During a longer stride, the body is generally allowed to fall more freely, taking some weight off the feet.

The fact that maximum ground reaction moment during walking was the highest with the MOLLE Standard probably relates to the relatively long stride length produced with that pack. Increased transverse rotation of the hips is typically characteristic of a longer stride, and that tends to rotate the foot outward, increasing ground reaction moment. Another effect apparently related to the longer stride length with the MOLLE is the greater knee flexion moment with the MOLLEs than with the SPEAR. With a longer stride, there is more resistance to knee flexion at heel-strike, necessitating greater knee flexion moment exerted by the muscles.

While the effect was not seen with walking, medial force and impulse were consistently higher when running with either MOLLE than with the SPEAR. This suggests greater medio-lateral body movement when running with the MOLLEs than with the SPEAR. There is no obvious reason for this, or for the higher vertical heel-strike force with the MOLLE Extended than with the SPEAR.

CONCLUSIONS

The MOLLE Standard pack can be characterized as medium in height above the belt, width, anterior-posterior dimension, and distance from the pack center of mass to the load carrier's back, with low impediment to rearward arm swing. The MOLLE Extended pack can be characterized as of medium height above the belt, wide, of large anterior-posterior dimension, with relatively great distance from the pack center of mass to the load carrier's back, and with medium impediment to rearward arm swing. The SPEAR pack can be characterized as tall in height above the belt, wide, of medium anterior-posterior dimension, with relatively small distance from the pack center of mass to the load carrier's back, and with high impediment to rearward arm swing. These characteristics largely account for the differences observed between the packs in walking and running kinematics and kinetics.

During walking, the MOLLE Standard produced the longest stride length, the highest braking, ankle, and knee forces divided by loaded subject weight, and highest ground reaction moment. During running, the MOLLE Standard produced the largest sagittal plane trunk angle range, greatest rearward arm swing and arm swing range, smallest lateral distance between the arms and trunk, lowest maximum upward center of mass velocity, lowest ankle angle range, greatest degree of knee straightening, and greatest degree of hip extension.

During walking, the MOLLE Extended produced the greatest amount of forward trunk inclination and the lowest hip-flexion torque. During running, it produced the greatest minimum lateral distance from the arm to the trunk, the highest center of mass upward velocity, the greatest ankle angle range, the least straightening of the knee, the most hip extension, and the highest hip flexion torque.

During walking, the SPEAR produced the shortest stride length, least rearward arm swing, most forward arm swing, greatest lateral distance from the arm to the trunk,

lowest peak downward velocity of the center of mass, lowest ankle and knee force divided by loaded subject weight, least unweighting during the stride, and the greatest knee and hip flexion torques. During running, the SPEAR produced the least forward trunk lean, the least trunk angle range, the least rearward arm swing, the greatest forward arm swing, the highest minimum and maximum positions of the center of mass during the stride, the lowest hip flexion torque, and the lowest medial forces and impulses.

Some of the significant differences between pack systems can be directly related to pack characteristics. For example, the MOLLE Standard had the least impediment to arm swing, which probably contributed to the longer stride length it produced. The longer stride length helps to explain the higher associated braking, ankle, and knee forces. The large rearward protrusion of the MOLLE Extended pack can account for the greater forward trunk inclination, which was needed to keep the center of mass over the feet. The high profile of the SPEAR helps explain the low forward trunk inclination it produced. Its large width explains its impediment to arm swing.

It appears that the only direct effects of pack volume were related to lateral protrusion that impeded arm swing. The other effects were indirect. For example, differences in pack center of mass likely accounted for several of the differences. If the packs were all filled uniformly, the SPEAR would have the highest center of mass, while the MOLLE Extended would have the most rearward center of mass. It appears likely that backpack center of mass location has a large impact on gait kinematics and kinetics. However, just because a pack protrudes rearward or upward does not mean that it has to be loaded such that the center of mass is located respectively more rearward or higher. For example, heavy items can be placed close to the wearer's back no matter how rearward the pack protrudes.

Moment of inertia, or resistance to rotational acceleration, tends to be higher in a backpack of higher volume, even if the weight is the same, because greater distances of point masses from the pivot point greatly increase moment of inertia. The SPEAR, being the tallest and most voluminous of the packs, likely had the greatest moment of inertia about the hip, which provided the greatest resistance to rotation and thus, the least trunk rotation in the sagittal plane. The MOLLE Extended, which had the second largest volume, produced the second lowest degree of sagittal trunk sway.

There appears little reason to do further research on the biomechanical effects of pack volume on running or walking in an open area, since volume appears to directly affect gait only when free arm swing is impeded, or when the pack itself impedes locomotion in narrow or oddly-shaped passageways. The effects of pack center of mass location have already been studied and its effects established. However, the effects of backpack moment of inertia have not been established and should be examined in the future.

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GLOSSARY

For readers interested in the biomechanics of load carriage, but unfamiliar with its terminology, the definitions below will be helpful for understanding this report:

1. **Cadence**. The frequency in which steps or strides are taken. Since two steps (one left, one right) are taken for every full stride, cadence expressed in steps per minute is twice as great as cadence expressed in strides per minute.

2. **Double-support Phase**. The period during a gait cycle when both feet are in contact with the ground at the same time; i.e., both feet are in their respective stance phases. Each complete gait cycle includes two double-support phases. One begins as the right heel strikes the ground, while the left foot is still on the ground. It continues as weight is shifted from the left foot to the right foot and ends when the toe of the left foot leaves the ground. The other begins as the left heel strikes the ground while the right foot is still on the ground. It continues as weight is shifted from the right foot to the left foot and ends when the toe of the right foot leaves the ground.

3. **Ground Reaction Force**. The force exerted by the ground on the foot, which is equal in magnitude and opposite in direction to the force exerted by the foot on the ground.

4. **Impulse**. The area under the curve of force as a function of time.

5. **Joint Torque**. The tendency to rotate adjacent bones around a joint, brought about by the activation of muscles crossing the joint. Quantitatively, joint torque is calculated as the product of muscle force and the perpendicular distance from the line of action of the muscle force to the pivot point of the joint.

6. **Kinematics**. Quantification of motion without regard for the forces producing the motion. Human kinematic data include linear and rotational position, velocity, acceleration, and range of motion for each body segment and the total body center of mass. It also includes such variables as stride length, stride frequency, and relative time in single- and double-support.

7. **Kinetics**. Analysis of the forces and torques that bring about motion. Human kinetic data include ground reaction forces, joint bone-on-bone forces, and muscle torques.

8. **Single-support**. The period during a gait cycle when only one foot is in contact with the ground; i.e., one foot is in its stance phase while the other foot is in its swing phase. A single-support period of the right foot begins at toe-off of the left foot and ends at the subsequent heel-strike of the left foot. Each complete gait cycle includes a single-support phase on each foot.

9. **Stance Phase**. The portion of a gait cycle when a given foot is in contact with the ground. It begins with the foot's heel-strike and ends with its toe-off. Each complete gait cycle includes a stance phase for each foot. The stance phase makes up about 60% of the walking gait cycle, with little variation attributable to the load carrier's age and height at normal backpack volumes (Murray et al. 1964, Smith et al. 1960).

10. **Stride Length**. The length of a full stride, which includes both a left and a right step. In this study, stride length was measured as the horizontal distance between the locations of two consecutive right heel-strikes.

11. **Stride Time**. The time for a full stride, which includes both a left and a right step. In this study, stride time was measured as the time between consecutive right heel-strikes.

12. **Swing Phase**. The portion of a gait cycle when a foot is not in contact with the ground. It begins with the foot's toe-off, continues as the foot swings forward, and ends with its heel-strike. Each complete gait cycle includes a swing phase for each foot. The swing phase makes up about 40% of the walking gait cycle, with little variation attributable to the load carrier's age and height at normal walking speed (Murray et al. 1964, Smith et al. 1960).